EFFECTS OF LIME, PHOSPHORUS, AND OTHER NUTRIENTS APPLIED TO TROPICAL SOILS AND A FLORIDA SPODOSOL ON GROWTH AND MINERAL COMPOSITION OF FORAGE LEGUMES

By

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To the Memory of my Parents,

Maria Elena

and

Manuel de Jesus

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Oven-dry *Centrosema pubescens* Benth. and *Trifolium repens* L. herbage and root yields from a Guatemalan Oxisol were increased by liming with 600 ppm of $CaCO_3$; lime rates of 1,200 and 1,800 ppm, however, markedly depressed yields. Phosphorus rates from 0 through 75 ppm markedly increased plant growth. Phosphorus applied at 50 and 75 ppm reduced the magnitude of lime-induced yield depressions, which suggested reduced P availability in this soil associated with liming. For a Florida Spodosol, legume yields increased linearly with increased lime rates through 1,200 ppm; thereafter, *Centrosema* yields were slightly reduced and those of *T. repens* remained constant. Lime-induced yield depressions were smaller for *T. repens* than for *Centrosema*. *Trifolium repens* did not grow on the unlimed Spodosol, but *Centrosema* grew to some extent.

Application of all essential plant nutrients except N did not ameliorate *Phaseolus lathyroides* L. and *Phaseolus atropurpureus* DC. (Siratro) lime-induced yield depressions from a Guatemalan Oxisol and a Costa Rican Entisol.

In greenhouse experiments, oven-dry *P. lathyroides* and Siratro herbage yields increased markedly with P rates through 200 ppm for the Oxisol and Entisol, and through 100 ppm for a Guatemalan Inceptisol. However, in field experiments at Izabal, Guatemala, *Centrosema*, Siratro, and *Stylosanthes humilis* L. herbage yields were not significantly affected from 0 through 200 kg/ha of P applied to the Oxisol and Inceptisol.

In general, liming increased Ca concentration in plant tops but did not affect P, Cu, or Fe concentrations. Manganese and Zn concentrations decreased markedly with increased lime rates. Lime effects on K and Mg concentrations, however, were not consistent among soils and plant species. Phosphorus fertilization increased P and K concentrations in plants; Mn and Zn concentrations, however, decreased with increased rates of applied P. The effect of applied P on Ca, Mg, Cu, and Fe concentrations in herbage and roots was not consistent among soils and plant species.

INTRODUCTION

Agricultural production is the foundation of economic growth and national welfare in many developing countries in the tropics. This is particularly true of Central America which was the region of main interest in this investigation. According to the Battelle Memorial Institute (32), the relatively high rate of economic growth of the Central American region over the past 10 years was primarily due to increased production of export crops such as bananas, coffee, sugar, and cotton. However, livestock-related industries have the potential of becoming a major contributing part of the agricultural sector. The total number of cattle in the region in 1965 was estimated at 7.4 million and total area under pasture at 6.4 million ha. Market prospects for animal products, particularly beef, in the United States and other countries with high standards of living are bright. Increased meat exports can bring needed foreign exchange to the region to pay for increased imports required for industrial development. The domestic market for meat is also expanding as a consequence of continuous increase in population and the great need for additional protein in the diet of most Central Americans.

All governments in Central America have recognized the need for fostering the development of animal husbandry in their countries. Considerable emphasis has been given to improvement of cattle breeds since native cattle prevalent in the region are small and yield little meat. However, practically all cattle are still pasture fed on grasses with high seasonal variability in nutritional value. The better pasture species now available generally supply adequate nutrition during the growing season, but their feeding value is very low during the dry season. The results of this situation are low stocking rates and weight losses which markedly extend the slaughtering age of animals.

A research program aimed at pasture improvement must be based on reliable data to define climate, soil, and economic potential of the region in order to select the areas with best prospects of increasing animal production. The agrostologist can then play a key role in the program by becoming involved in at least three broad areas: definition of factors controlling pasture productivity, quality, and persistence; selection of the best pasture species for each area and evaluation of their nutritive value to animals; and development of superior pasture management systems.

Tropical pasture legumes can play a key role in increasing animal production in the tropics. They can build up the nitrogen status of soils and provide protein directly to the animal. This would result in increased production and improved quality of the pasture, particularly during the dry season. The Australians have done extensive research on pasture systems based on tropical legume-grass combinations over the past 20 years. According to Henzell (168), the main objective of this research effort has been achieved, i.e., substantial increases in commercial livestock production with the inclusion of legumes in the pasture. Many of these legumes are native to the Latin American tropics, but their potential as forage plants was largely ignored in the past.

In the final analysis, the soil-plant-animal systems is part of a complex biological cycle that begins and ends with the soil as the ultimate source and reservoir of nutrients; hence the great importance of soil studies in pasture improvement. Soil conditions in the tropics have not been studied so extensively as in temperate regions. Present knowledge indicates, however, that althoguh tropical soils exhibit a wide range of physical and chemical properties, some soil conditions such as high acidity and low P availability are prevalent over large areas. The effect of liming tropical soils at low rates has generally been beneficial in soils with low supply of available Ca, and particularly soils with high content of exchangeable Al below pH 5.5. Liming to pH values higher than 6 has generally resulted in depressed yields which have been associated with decreased micronutrient and P availability and structural deterioration. Many tropical soils with high contents of amorphous Fe and Al hydrous oxides or allophanic materials fix large amounts of applied P, and consequently are extremely deficient in this element for optimum crop production.

Based on considerations previously mentioned, the present investigation was undertaken with the following objectives in mind:

1.- To characterize the physical, chemical, and fertility status of three tropical soils, particularly in relation to growth of tropical legumes.

2.- To study nutrient composition interrelationships of a tropical legume with different combinations of nutrients applied to three tropical soils.

3.- To compare the response of a tropical and temperate legume to lime and P applied to a tropical Oxisol and a Florida Spodosol.

4.- To study the effect of major, secondary, and micronutrient applications to two tropical soils on the response of tropical legumes to liming.

5.- To determine P-retention capacities of three tropical soils and a Florida Spodosol by laboratory methods, and to correlate these results with the response of tropical legumes to P fertilization in the greenhouse and in the field.

REVIEW OF LITERATURE

The Chemical Nature of Soil Acidity

A soil becomes acid primarily by the removal of adsorbed bases from soil colloids through leaching and plant uptake, application of acid-producing fertilizers to the soil, root and microbial respiration, and microbiological oxidations (such as those involving S, Fe, Mn, and NH_4^+). Most of the processes mentioned above are particularly intensive in tropical regions due to their high rainfall and temperature regimes, and the high permeability of many of the soils, e.g., Oxisols and Inceptisols (Andepts).

Soil Reaction and pH

Soil acidity and alkalinity are measured on the pH scale, postulated by Sorensen in 1909. The pH concept was first proposed for aqueous solutions. It was defined as the negative logarithm of the H ion activity expressed in moles/liter. The soil pH measurement has remained the most important single diagnostic tool in soil analysis. However, the complexities of the soil system have made its interpretation uncertain in terms of H ion activity.

Several factors are known to affect the pH measurement of soils; the soil-water ratio used in the determination is one of them. Upon infinite dilution, the reaction of a soil suspension approaches that of water. The soil-water ratio also decreases the magnitude of the suspension effect; this term refers to the lower pH value usually obtained in a soil paste as compared with that in the supernatant solution. A narrower soil-water ratio allows more intimate contact between the pH meter electrodes and the adsorbed acidity on the colloidal particles; this causes lowering of the pH (234). An alternative interpretation of the suspension effect was offered by Coleman et al. (94). Dissolved salts in the soil also influence the pH due to their effect on the electric double layer around soil particles. Cations and anions from the dissolved salts mix with exchangeable cations in the double layer and make it less diffuse; as it becomes less diffuse, the H ion concentration difference across the double layer is reduced, and the pH of the suspension falls (313).

A 1:2.5 soil-water ratio was adopted in 1930 by the Soil Reaction Committee of the International Society of Soil Science (281). Measuring the pH of the soil in a salt solution removes any uncertainty about the suspension effect. Many European scientists measure soil pH in 1N KCL; this value includes some of the exchange acidity and may be 1 to 2 pH units lower at low pH values than that measured in water (281). Schofield and Taylor (324) proposed measuring the pH in 0.01M $CaCl_2$. A 0.01M $CaCl_2$ solution is approximately equivalent to the total electrolyte concentration of the soil solution of a non-saline soil at optimum field water content (324). The pH value measured in 0.01M $CaCl_2$ may be 0.5 pH unit lower at low pH values than that measured in water (313). Schofield and Taylor (324) indicated that the value pH - 0.5pCa remains constant for any given soil for a wide range of concentrations of $CaCl_2$ in the soil suspension; they called this value the lime potential. The same authors (324) suggested that pH values be expressed as lime potential values by subtracting 1.14, the value of 0.5pCa for 0.01M $CaCl_2$, from the observed pH value.

The pH values of calcareous soils are closely related to the partial pressure of CO_2 in the soil atmosphere, the concentration of HCO_3^- and the ionic strength of the soil solution (388). According to an equation postulated by Bradfield (52), the relationship between pH of calcareous soils and logarithm of the partial pressure of CO_2 is linear with negative slope. Therefore, in the absence of appreciable exchangeable Na^+, the pH of a calcareous soil falls from 8.5 at the CO_2 pressure of air to 8.0 at a pressure of 0.002 atm, and to about 7.5 at 0.02 atm (52); CO_2 pressures in excess of these are not rare in soils. The effect of the CO_2 pressure on pH is very small below pH 7.0 (281).

Aluminum and Soil Acidity

As early as 1904, T. B. Veitch of the USDA Bureau of Chemistry found that neutral salt extracts of acid soils contained Al, Fe, and Mn (192). Japanese scientists followed with similar results in 1908 (192).

In 1923, from potentiometric and conductimetric titration curves, Bradfield (51) postulated that acid clays were weak acids, similar in electrochemical properties to acetic acid. This theory was capable of explaining pH, hydrolytic acidity, exchange acidity, and $AlCl_3$ in soil extracts. It was proposed that H^+ was replaced from the clay by the neutral salt and immediately dissolved hydrated alumina in the soil, causing Al to appear in the extract (100). The concept of an acid clay as an H-saturated clay prevailed among soil scientists for a long time, particularly in the United States.

In 1933 Paver and Marshall (276) proposed that electrodialyzed bentonite and Putnam clay were Al saturated. In Russia, Chernov (79) reported his findings concerning soil acidity in 1947. Chernov found that if a soil is treated with HCl and then extracted with KCl, both H and Al ions were always present; furthermore, if the soil was allowed to reach equilibrium, after removal of HCl excess, the content of Al ion increased and that of H ion decreased. Later findings by Chernov, Beliaeva, and Maximova (80) seemed to indicate that the rate of replacement of Al for H ions in acid clays was a function of time, temperature, and the nature of the adsorption complex. The Russian soil scientists (80) found that the relationship between H/Al ionic ratio and time was hyperbolic; the rate of replacement was very sharp at first but later decreased at a slower rate.

In 1949, Schofield (323) studied the cation and anion exchange properties of some Rothamstead soils and postulated that Al ion was the main constituent of soil acidity. In 1950, according to Jenny (192), Russell included Schofield's ideas in the eighth edition of his book "Soil Conditions and Plant Growth." In the 1950's more evidence supporting the Al theory started to accumulate in the United States. Coleman and Harward in 1953 (87) and in 1954 (160) compared heats of neutralization, and conductimetric and potentiometric titration curves of H- and Al- resins with those of acid soil clays; they came to the conclusion that the main constituent of acid clays was Al. These authors (87, 160) also observed that H-clays changed to Al-clays upon moist storage supporting earlier similar findings by Chernov et al. (80). In 1955, Low (222) published a classic paper showing that conductimetric and potentiometric titrations could differentiate between adsorbed H and Al ions; this author showed then that electrodyalized bentonite was Al saturated and that acid-washed clay had both H and Al ions. It is now an accepted fact that H-clays are strong acids but very unstable; they become Al saturated quickly, the rate of reversion being a function of time, temperature, the nature of the adsorbing complex, and electrolyte concentration (79, 80, 87, 100, 160, 192, 222).

It is interesting to note that the same type of data used to postulate the H theory of soil acidity was also used to disprove it; the only difference was the interpretation made of the data. For example, the predominance of Al ion on the adsorption surface of electrodyalized clays accounts for the early conclusion reached by Bradfield (51) that acid clays were weak acids. Trivalent Al, or aluminohexahydronium ion according to Jackson's nomenclature (188), is a weak acid with a pK of 5, similar to acetic acid with a pK of 4.7, which was the acid Bradfield used for comparison with acid clays.

Exchange Properties of H and Al

The discovery that acid soils are primarily Al saturated created the need for more information on the exchange properties of the Al ion. Also, the spontaneous transformation of H-clays to Al-clays raised questions concerning the validity of early work on the exchange properties of the H ion. Coulter (100) reviewed recent work on the subject. Aluminum appears to be adsorbed very strongly on soils and clay minerals; the extent of adsorption is a function of clay mineral type but not so much of organic matter content (85). Montmorillonite seems to adsorb Al ions more strongly than K^+. However, vermiculite, illite and some soils show preference for K^+; evidence suggested that in the latter cases K^+ may reside within the clay lattice where it is difficult to exchange for other ions (100). Hydrogen exhibits exchange properties similar to the alkali metals. The place of the H ion in the alkali-metal lyotropic series depends to some extent on the exchanger but seems to fall between Na^+ and K^+ (145). McLean, Heddleron, and Post (242) placed H^+ at the end of the K^+, Na^+, NH_4^+ lyotropic series; they used a Dowex 50-8x resin as exchanger. Hydrogen ions are very weakly adsorbed compared to Al ion (100); this may explain why H-clays are unstable and revert spontaneously to Al-clays.

Sorbed Forms of Al in Acid Soils

One form of Al in soils can be extracted by leaching the soil with a salt of a strong acid such as normal solutions of KCl, $CaCl_2$ and NaCl (214); the leachate contains Al in trivalent form (214, 300, 354). Simple trivalent Al ion has strong affinities for O and OH ions and should be difficultly exchangeable (192). This means that trivalent Al is hydrated octahedrally when adsorbed on clay surfaces, and consequently less strongly held than the non-hydrated trivalent Al ion. Jackson (188) proposed the name aluminohexahydronium for this ionic species. The aluminohexahydronium ion acts as a weak acid with a pK of 5 as mentioned earlier (188); at pH 5, this ionic species is 50% dissociated, 5% at pH 4, and 0.5% at pH 3.0. Thus, the presence of intermediate Al hydroxides in acid soils is insignificant at pH values below 4. For example, the second pK for the aluminohexahydronium ion is 10, and consequently the concentration of dehydroxyaluminum ion is less than $10^{-9}M$ in solution in the pH range of soils (188). According to Jenny (192), the KCl replacement series for these hydroxy forms of Al would be $Al(OH)_2^+ > Al(OH)^{2+} > Al^{3+}$. Because of their ease of replacement, their presence would be indicated in the KCl extract; the fact that the stochiometric titration of KCl extracts shows only trivalent Al ion present is proof of their scarcity in soils. Thomas (354) presented data that suggested the formation of charged intermediate hydroxy-Al compounds such as $Al(OH)_2{}^+$ or $Al(OH)^{2+}$ with liming. These ions appear to be in such form that they can be neutralized to $Al(OH)_3$ by a high concentration of OH ions but cannot be replaced from exchangers by unbuffered salt solutions. In view of Jenny's KCl-replacement series (192), the hydroxy-Al ions mentioned by Thomas (354) could only exist in a nonexchangeable form in the interlayer spaces of the clay. McLean (240) stated that these hydroxy-Al compounds could be adsorbed on exchange sites in the soil more strongly than trivalent Al; this contradicted earlier experimental findings by Jenny (192) as mentioned previously.

Sorbed Al can also be found in the interlayer space of 2:1 clay minerals. The evidence for the existence of alumina interlayering has been reviewed by several authors (91, 100, 188, 291, 300) and can be summarized as follows: clays interlayered with hydroxy-Al compounds occur widely in both acid and alkaline soils (188); additional adsorption of Al from solution by Al-saturated montmorillonite at an activity product less than that for gibbsite (291); Al adsorbed by vermiculite inhibited glycol and glycerol retention and $NH_4{}^+$ fixation but could be removed by alkaline extraction (300). The CEC of these interlayered clays are usually smaller than would be expected for the pure layer silicate (91). Removal of the interlayer material by NaOH treatment increases the CEC and restores the expansion-contraction properties of the layer silicate (300). Rich (300) postulated that the Al interlayers consisted of positively charged hydroxy-Al polymers having a neutralizing effect on the negative permanent charge of clays. This hypothesis has found support from other experimental results (100, 183, 188, 216). Studies of Al artificially fixed in clay minerals and resins suggest that interlayer alumina is a hydroxy-Al polymer with composition ranging from $Al_6(OH)^{6+}{}_{12}$ to $Al_n(OH)_{3n}$. A hexagon or ring structure has been postulated for these polymers by Hsu and Bates (183). These authors indicated that the positive charge of the polymer would increase from a 6^+ charge in $Al_6(OH)^{6+}{}_{12}$ (at a pH below 4) to 18^+ in a 19-ring polymer structure (at a pH around 7). The net positive charge per Al in the polymer would decrease with increasing pH; it would be 1^+ at a pH below 4 and would decrease until completely neutralized (charge of 0^+/Al) at a pH around 8. At this pH value the repulsion among polymers, due to their positive charge, would disappear and they would cluster together to form crystalline $Al(OH)_3$.

Some workers (90, 334) have synthesized hydroxy-Fe interlayers in clays and have noted that they have properties similar to those of clays interlayered with hydroxy-Al polymers. Thomas and Coleman (355) observed that the hydrolysis of Fe in acid soils resulted in the formation of interlayer hydrous Fe oxides.

In volcanic ash soils, Al also exists in an amorphous mixed-gel material called allophane, composed mainly of Si and Al in mole ratios between 0.5 and 1.3 (91, 100, 189). According to Russell (313), allophane is typically the first weathering product of some type of volcanic ash; as time proceeds, it becomes more crystalline until it eventually becomes the clay mineral kaolinite.

Soil Acidity Components

Acidity in soil systems can be conveniently classified as active and potential acidity (89, 313). Active acidity includes H ions in the soil solution and is usually measured potentiometrically with a pH meter. Potential acidity may be measured approximately by a total titratable acidity determination; it constitutes the bulk of the acidity of the soil. Equilibrium exists between active and potential acidity. The relative magnitude of each acidity component depends on the nature of the colloidal material and the degree of neutralization of the system.

Potential acidity can not be measured accurately by the methods now in use; part of the acidity of the soil reacts with lime but does not react with the buffer solutions (329). One method by which total acidity is often determined is that developed by Mehlich (244). The soil is extracted with $BaCl_2$-triethanolamine buffered at pH 8.2 and the extract is titrated with standard acid. Triethanolamine is a weak base with a pK_b of 7.8, well buffered at pH 8.2.

Exchangeable acidity, that which can be extracted by a neutral salt solution, can be determined using a 1N KCl solution as described by Coleman, Weed, and McCracken (93). This component of soil acidity consists of Al and H ions, particularly the former, adsorbed electrostatically on exchange sites of the soil system.

Nonexchangeable acidity, or pH-dependent acidity as it has been called by Coleman et al. (93) and Pratt (289), can be extracted with $BaCl_2$-triethanolamine at pH 8.2 after extraction with KCl (289). The sum of exchangeable acidity and pH-dependent acidity constitutes total titratable acidity for a particular soil.

The exchangeable acidity in acid soils consists mainly of trivalent Al ions (93, 214, 240, 300, 354). There exists a linear relationship between pH and $AlCl_3$ in aqueous solutions (389). The pH of the solution may indicate the Al ion concentration. This relationship is more difficult to establish in soils due to the presence of adsorptive surfaces, which reduce the activity of the Al ion, and H ions from other sources,which reduce Al hydrolysis by common ion effect (389). Popenoe (287) found that exchangeable Al was closely related to the pH of Polochic Valley soils in Guatemala. He found that exchangeable Al existed in significant amounts only in soils with pH less than 5.0; however, very acid soils having more than 25% organic matter had much less exchangeable Al than soils of comparable pH with less organic matter. On the other hand, Clark and Turner (85) found no direct relationship between pH and either extractable (with NH_4OAc at pH 4.8) or exchangeable Al in some acid soils.

Hydrogen ions seem to be present in appreciable amounts only in very acid soils or in combination with large amounts of organic matter. Coleman et al. (93) found that exchangeable acidity was caused by Al ions and a negligible amount of exchangeable H ions. Thomas (354) concluded that the acidity extracted with a 1N NaCl solution was caused entirely by Al ions. Yuan (389) reported that titration curves of 1N KCl extracts of some Florida soils showed that very acid soils, pH less than 4.8 in KCl, had more H than Al ions; at higher pH values there were more Al than H ions, both ions becoming negligible at about pH 5.8. The soils used by Yuan (389) were sandy with low CEC values primarily arising from organic matter. Coulter

(100) found in soils limed at different rates that at pH 3.1 (measured in 0.01M $CaCl_2$) there were 1.1 and 7.2 meq/100 g of H and Al ions, respectively. At about pH 4.8, exchangeable Al was only 0.2 meq/100 g and H^+ was negligible. Thomas (354) indicated that little exchangeable acidity or Al is extracted from a soil above pH 5.3. Similar results have been reported by McLean et al. (241). In some cases, it appears that when a soil is initially high in exchangeable Al and it is limed, appreciable amounts of exchangeable Al remain extractable (240).

Coleman and Thomas (91) stated that the ratio of exchange acidity to total acidity decreases in the series montmorillonite, dioctahedral vermiculites, kaolinite. In soils containing appreciable amounts of organic matter, the proportion of exchange acidity is usually very low. This is because the CEC of organic matter is low in very acid soils and is usually countered by Al and Fe ions, which are difficult to displace with a salt solution (91). Aluminum and Fe hydrous oxides, either as surface coatings or in interlayer spaces of clays, reduce the proportion of exchangeable acidity (90, 92, 214); this is expected as hydrous oxides are usually positively charged in acid soils and neutralize negative charges on the clay.

The exchange acidity determination does not include that part of the total titratable acidity of the soil due to weakly ionized acidic groups in soil minerals and soil organic matter. This kind of acidity is called nonexchangeable or pH dependent. The source of pH-dependent acidity can be attributed, at least in some cases, to organic matter. However, in many instances soils or subsoils with a low content of organic matter show a high proportion of pH-dependent acidity (92, 93, 289); this is particularly true of many soils in the Ultisol and Oxisol groups (92, 93). Mineralogical samples of clay minerals do not show appreciable pH-dependent charges (313, 323) and could not account for pH-dependent acidity. The classical explanation advanced by Schofield (323), implicating the dissociation of H^+ from SiOH groups around clay edges, is not likely to play a role since SiOH functions as a weak acid with a pKl of 9.5 (188, 326). Probably the most likely sources of pH-dependent acidity, not due to organic matter, are Al and Fe hydrous oxides; these compounds are positively charged below pH 8.0 and exist in interlayer spaces of 2:1 clays and as surface coatings on kaolinite (90, 92, 189, 300, 326).

The terms exchangeable, nonexchangeable, and total titratable acidity have been used here as defined by Coleman et al. (92, 93), Pratt (289), and Coleman and Thomas (91). The term exchange acidity has also been used by Peech (280) to denote acidity extracted by buffered salts such as $BaCl_2$-triethanolamine at pH 8.2 or NH_4OAc at pH 7.0; this use of the term was considered confusing and was consequently ignored.

Lime Requirement

Theoretically, the ideal analytical method for the determination of lime requirement would be that which gave an accurate estimate of the potential acidity of the soil at the desired pH. Lime requirement has been defined as the amount of lime required to raise the pH of the soil to a prescribed value, usually in the range of 6.0 to 7.0 (313).

Soil pH and percent base saturation have been used to calculate the lime requirement of soils (243). This method has limited use because the relationship between pH and percentage base saturation differs greatly from soil to soil. In many tropical soils this relationship does not exist; these soils are strongly acid and exchangeable bases have been leached from the soil.

More precise methods of determining lime requirement use strongly buffered solutions. For example, paranitrophenol buffered at pH 7.0 was suggested by Schofield (322). When the solution is added to an acid soil, it reacts and reaches an equilibrium pH value; the magnitude of the pH depression, being directly related to the amount of acidity in the soil, can be converted to a lime requirement value. The Woodruff method uses a mixture of $Ca(OAc)_2$-p-nitrophenol-MgO buffered at pH 7.0. The buffer solution is mixed with the soil and lowers its pH by 0.2 unit for each ton of lime required by the soil (187). Shoemaker, McLean, and Pratt (329) pointed out that the Woodruff method did not give an accurate estimate of the lime requirement of some acid soils from Ohio with appreciable amounts of extractable Al. These authors (329) developed an improved buffer method which they claimed was adequate for soils with much clay-sorbed hydroxy Al. One shortcoming of buffer methods is that, for weakly buffered soils, the pH depression can be insignificant compared with the error of measurement.

Barium chloride-triethanolamine buffered at pH 8.2 (233) has also been used extensively to estimate the lime needs of soils. This method is also used to determine total titratable soil acidity and was described in the preceding section. Perhaps its most serious shortcoming is that soils are not limed to pH 8.2 and, therefore, it is difficult to interpret in terms of actual lime requirement of the soil at the desired pH value. A method which has the rationale of neutrality is $Ca(OAc)_2$ buffered at pH 7.0 (187). This solution is allowed to react with the soil and the filtrate is titrated to pH 8.3 for a sharp end point.

Bradfield (52) suggested titrating the soil with $Ca(OH)_2$; increments of the base are added to the soil and allowed to incubate. Excess $Ca(OH)_2$ precipitates as $CaCO_3$, and the titration curve reaches a plateau level at pH 8.2. The amount of $Ca(OH)_2$ added to reach that plateau is considered to be equivalent to soil acidity.

All methods now in use for determining lime requirement may be subjected to error due to the incomplete neutralization of soil acidity in some soils. Shoemaker et al. (329) indicated that some form of Al in acid soils from Ohio reacted with lime but did not react with the $BaCl_2$-triethanolamine buffer used to determine total acidity. They suggested that the sudden change in pH produced when the buffer was added to the soil caused some Al to be trapped in the clay lattice by precipitated $Al(OH)_3$.

Recently, Kamprath (202) and Reeve and Sumner (297) used another approach to liming acid soils, adding only enough lime to neutralize exchangeable Al in the soil and supply Ca and Mg. This approach is based on the assumption that two fundamental benefits derived from liming are reduction of exchangeable Al to non-toxic levels and supply of Ca and Mg to the soil. Kamprath (202) recommended liming at a rate equivalent to 1.5 times the exchangeable Al; he suggested using a factor of 2 with plants that are very sensitive to Al. The factors 1.5 and 2 are expected to reduce Al saturation to around 15 and 5%, respectively. These values were calculated from experimental data using four North Carolina Ultisols.

All these methods estimate lime requirement in terms of amount of Ca required to raise soil pH to a desired level. In order to estimate the amount of limestone required, a liming factor must be used because limestone added in the field does not raise the pH as much as predicted by the testing procedure. This factor varies from 1 to 3 depending on the rate of limestone solution, plant uptake, and leaching during the reaction period (313).

Cation Exchange Properties of Acid Soils

Schofield (323) found that the CEC of clay subsoils from Rothamstead remained constant between pH 2.5 and 5 but increased between pH 5 and 7. He introduced the term "permanent charge" to mean the lattice charge developed in clay minerals by isomorphous substitution which remains constant regardless of pH. According to Russell (313), kaolinite exhibits a low CEC of around 3 or 4 meq/100 g but values as high as 15 meq have been reported. Halloysite has a similar low value. Micaceous clays have larger CEC values, namely: illites may have from 10 to 40, montmorillonites from 50 to 60, vermiculites from 100 to 150, and chlorites from 10 to 40 meq/100 g. The CEC of these clay minerals arise from permanent charges, and there is little pH-dependent charge (91, 189, 313, 339, 381). However, when the CEC of soils is measured at different pH's, it is found that it changes with pH, especially in the range between pH 5 and 8. For example, data reported by Bhumbla and McLean (40) showed that liming some acid soils in Ohio from around pH 4 to approximately pH 6 to 7 increased CEC values, measured with KCl, some two-fold. Coleman et al. (93) found that in some North Carolina acid soils CEC at the pH of the soils was from 30 to 50% of the CEC at pH 8.2. Fiskell et al.

(128) reported that the CEC of some North and Central Florida soils were twice as large at pH 7.0 as at pH 4.8.

Undoubtedly, organic matter is responsible for a large part of the pH-dependent CEC of soils. Broadbent and Bradford (58) stated that the CEC of organic matter is near zero at pH 3 or 4, and it increases linearly until it reaches pH 8. At this pH, organic matter generally shows a CEC of approximately 200 meq/100 g; this value decreases to around 100 meq/100 g at pH 6 (58).

According to Schnitzer and Gupta (321), the CEC of organic matter below pH 7 arises from dissociation of carboxyl groups; at higher pH values, phenolic groups and, to a lesser extent, enolic and imide groups become important contributors.

For many years it was believed that the ion exchange properties of a soil were due entirely to clay and silt fractions and the organic matter component of soils. However, in recent years it has become apparent that interlayering and surface coating of clays with Al and Fe oxides play significant roles in determining the CEC of soils (90, 92, 183, 189, 300, 326).

Coleman et al. (92) found that neutralization of $AlCl_3$ and $FeCl_3$ salts with NaOH in a bentonite suspension resulted in the formation of clay-sesquioxide complexes. They showed that when two-thirds of the Al or Fe was neutralized with base the CEC of the system was reduced drastically. For example, the CEC was reduced from 73 to 6 meq/100 g when 12 meq of Al were added to 1 g of clay suspension and partially neutralized with 8 meq of NaOH. In the same study, hydroxy Al was somewhat more effective than hydroxy Fe in reducing the CEC of the system. Completely neutralized samples had substantially larger CEC than partially neutralized mixtures, but their CEC was still appreciably below that of bentonite. The effect of the sesquioxides on the CEC of the system could be reversed by titration with NaOH to pH 8 to 9. In summary, the work of Coleman et al. (92) showed that the synthetic bentonite-sesquioxide complex exhibited large pH-dependent components of CEC similar to acid soils high in Al and Fe oxides. It has been postulated by many authors (90, 92, 189, 300, 326) that Al and Fe hydrous oxides are positively charged at low pH and consequently they neutralize the lattice charge on the clay mineral. As the pH increases, the hydroxy-sesquioxide material gains OH ions and loses positive charge, freeing exchange sites on the layer silicate. Therefore, the effective CEC of the clay will be some value between the lattice charge of the mineral and zero.

This new knowledge is of consequence in many respects. For example, Coleman et al. (93) called the sum of cations displaced by 1N KCl "permanent charge." This is generally incorrect because in many soils CEC measured by neutral salt leaching is not equivalent to isomorphous substitution charge. In soils with appreciable amounts of Al and Fe oxides, CEC determined by neutral salt leaching represents the net charge after negatively charged clays and positively charged hydrous oxides.

A significant part of anion adsorption can develop on positively charged hydrous oxides. Anions such as Cl^-, SO_4^{2+} and $H_2PO_4^-$ can be held in a hydroxy-Al or hydroxy-Fe structure in substitution for OH ions. Significant Cl^- and OAc^- retention in soils with interlayer Al has been reported by Rich (301).

Cation exchange capacity determined with $BaCl_2$-triethanolamine buffered at pH 8.2 could give a close estimate of the permanent charge of layer silicates if the soil is free of allophane, and if organic matter is removed.

The addition of KCl to a soil suspension, in the pH determination, may result in both cation and anion exchange reactions. The K cation can displace H^+ and Al ions from the negatively charged clay mineral surface; at the same time the anion can replace OH ions from the hydroxy-Al or hydroxy-Fe polymers. Therefore, the resulting pH (KCl) can be lower, equal or higher than the pH(H_2O). In most cases pH(KCl) is lower than pH(H_2O). However, Bennema (36) indicated that in some soils with very low amounts of silicate clay minerals, classified as "Acrox" in the 7th Approximation, the pH(KCl) is greater than the pH(H_2O). These soils are rare but occur, among other areas, in South Africa and Latin America.

Neutralization of Soil Acidity

When lime is applied to an acid soil, $CaCO_3$ dissolves slightly. Through mass action, Ca ions displace H and Al ions from exchange sites. Aluminum hydrolyzes and produces more H ions. Bicarbonate ions react with H ions to neutralize the acidity. These reactions can be depicted as follows:

1. Dissolution of $CaCO_3$ (327)

   $CaCO_3 + H_2O + CO_2 = Ca^{2+} + 2HCO_3^-$

2. Displacement of H and Al ions

   $R\text{-}H + Ca^{2+} + H_2O = R\text{-}Ca + H_3O^+$

   $R\text{-}Al + Ca^{2+} + 6H_2O = R\text{-}Ca + Al\ (H_2O)_6^{3+}$

3. Hydrolysis of Al ions

$Al\ (H_2O)_6^{3+} + H_2O = Al\ (H_2O)_5(OH)^{2+} + H_3O^+$

$Al\ (H_2O)_5(OH)^{2+} + H_2O = Al\ (H_2O)_4(OH)_2^+ + H_3O^+$

4. Neutralization of H ions

$H_3O^+ + HCO_3^- = H_2CO_3 + H_2O$

$H_2CO_3 = H_2O + CO_2$

Jackson (188) indicated that below pH 5.6 the buffering capacity of mineral soils depends primarily on exchangeable Al. Exchangeable H ions can also contribute to soil acidity in some soils (389). Kamprath (202) pointed out that lime additions of less than the amount required to neutralize the exchangeable Al of four North Carolina Ultisols reacted primarily with exchangeable Al, causing the average pH to change from 4.6 to 5.3. Liming at a rate between 1.0 and 1.5 times the exchangeable-Al equivalent reacted with approximately equal quantities of exchangeable and nonexchangeable acidity. Lime in excess of 1.5 times the exchangeable-Al equivalent reacted solely with nonexchangeable acidity such as H^+ from Al and Fe hydrous oxides and carboxyl groups of organic matter.

Complete neutralization of Al ions with formation of $Al(OH)_3$ probably does not occur below pH 8; as the neutralization proceeds, hydroxy-Al ions start to polymerize, as postulated by Hsu and Bates (183). The polymerization of Al into a 6-member ring can be depicted as follows (80): $6Al(H_2O)_4(OH)_2^+ = Al_6(OH)_{12}^{6+} \cdot 12H_2O + 12H_2O$.

Liming and Plant Growth in Acid Soils

The response of acid soils to liming is due to a complex interaction of many factors. The emphasis in the literature has been mainly on soil-plant relationships involving P, Ca, Al, Mn, micronutrients, microbiological processes, and structure deterioration. These and other related aspects will be discussed here separately for convenience. However, one must keep in mind that all or some of them may occur simultaneously.

Hydrogen Ion Toxicity

High acidity in a soil is caused by high H ion activity in the soil solution. Earlier investigators attributed the beneficial effect of liming to neutralization of H ions, considering H ion toxicity as the main cause of acid soil infertility (22, 190). This led many investigators to propose optimum pH values for some crops (22). However, H ion activity in the soil solution per se is not a major cause of acid soil infertility within the pH range commonly found in soils (22). Arnon and Johnson (22) found that, provided all nutrients were adequately supplied, plant growth in solution culture was little affected between pH 4 to 8. These authors grew tomato (*Lycopersicon esculentum* Mill.), lettuce (*Lactuca sativa* L.), and bermudagrass (*Cynodon dactylon* (L.) Pers.) and found adverse effects of H or OH ion activity only at extreme values of acidity or alkalinity, pH 3 and 9. They postulated that one possible cause of injury from extremes of H or OH ion activity may have been interference with nutrient absorption. This hypothesis was supported by Arnon, Fratzke, and Johnson (21) who found a reciprocal relationship between H ion activity in the nutrient solution and extent of Ca absorption by tomatoes. The plant seemed to require a greater supply of Ca at low pH values than at neutrality. Other reports of depressed Ca absorption by plants growing in culture solutions at low pH have been recorded (219, 259, 260, 347).

Calcium Deficiency

Visual symptoms of Ca deficiency have been described by Wallace (374) and Chapman (75). Root growth is impaired; plant tops may show wilting and collapsing of young stems, petioles and pedicels; leaflets become chlorotic and have scorched margins; there may be dieback of the terminal buds.

In Australia, lime has been used to correct Ca deficiency in soils of the coastal lowlands of Queensland (13, 15, 68). Andrew and Norris (15) reported that humic gley soils from that area are acid, pH 5.5, and of extremely poor fertility status; exchangeable Ca can be as low as 0.1 meq/100 g, or approximately 3% of the total exchange capacity. Andrew and Norris (15) obtained maximum yields of ten tropical and temperate legumes with 600 to 800 kg/ha of lime. Lime rates beyond 1,000 kg/ha were of no further benefit. Russell (315) obtained significant yield increases by _T. repens_ (_Trifolium repens_ L.) from application of 2,000 kg/ha of lime to an acid, pH 5.5, solodic soil in southern Queensland. This soil had very low contents of P, K, and Ca (0.1 to 0.5 meq Ca/100 g, or 1 to 10% Ca saturation). The effect of lime in correcting Ca deficiency has also been observed on acid peaty sands of Western Australia (130).

Florida's flatwood soils are sandy, acid Spodosols, low in nutrient content, including Ca (0.5 to 1.0 meq Ca/100 g, or 15 to 30% Ca saturation). Gammon and Blue (141) and Blue et al. (45) have indicated that T. repens - grass pasture establishment on Florida flatwood soils requires a liming program with 4,480 kg/ha of lime at the time of establishment followed by 2,240 kg/ha of lime every 4 to 6 years to maintain adequate exchangeable Ca and pH levels. On Florida soils of coarse texture and low exchange capacity, an exchangeable Ca level of approximately 1,000 kg/ha (500 ppm) and a soil pH of 6.0 has been found adequate to produce top *T. repens* yields (175).

Large areas of acid soils under savanna or "Campo Cerrado" exist in Central Brazil with low levels of P and exchangeable bases. Calcium levels range from 1 meq/100 g, or 20% Ca saturation, to traces. These soils probably would be designated as Oxisols and Ultisols (136, 200) and are very responsive to lime applied in conjuction with NPK fertilizers (136, 200, 239). Jones and Freitas (200) reported that on these soils, *S. humilis* (*Stylosanthes humilis* H. B. K.) produced maximum yields at a lime rate of 625 kg/ha. *Centrosema* (*Centrosema pubescens* Benth.), *Glycine javanica* L., and Siratro (*Phaseolus atropurpureus* DC.) attained maximum growth at a rate of 2,500 kg/ha of lime; higher lime rates depressed yields of all legumes. This yield depression apparently was not related to a nutrient imbalance due to excessive concentration of Ca ions. Plant analyses indicated that the concentrations of Mn, Fe, Cu, Zn, and B, as well as that of macronutrients, were within normal limits. Mikkelsen, Freitas, and McClung (247) found that maximum growth of cotton (*Gossypium hirsutum* L.) on an Ultisol similar to those used by Jones and Freitas (200) was attained with application of 4,000 kg/ha of dolomitic limestone. Freitas and Pratt (137) working with four acid Ultisols and four acid Oxisols, found that both Siratro and *Stylosanthes gracilis* H.B.K. yields were reduced when liming raised pH values above 6.2. Jones, Freitas and Mohrdieck (199) obtained 3- to 6-fold yield increases for six temperate grasses when an acid Ultisol from southern Brazil was limed with 1,000 kg/ha of limestone. The authors indicated that the response to lime was due primarily to increased Ca supply in the soil.

The importance of lime in supplying Ca to plants growing in acid, Ca deficient soils is well documented in the literature. In general, these reports deal with sandy acid Spodosols such as those found in Florida (45, 141, 178) or in Australia (13, 15, 68, 315), or Ultisols and Oxisols such as those in Central Brazil (136, 137, 199, 200, 239, 247). These soils usually require only small rates of lime, under 1,000 kg/ha, unless the plant is relatively inefficient in utilizing Ca from the soil, or the Ca status of the soil is complicated by other factors such as leaching or Mn and Al toxicities.

Legumes are generally considered to have higher Ca requirements than cereals or grasses (308, 382). Loneragan and Snowball (221) determined Ca concentrations in 30 legumes, grasses, and cereals growing in culture solutions with a wide range of Ca concentrations. The average optimum concentration of legumes, 0.1 to 0.2% of dry weight, was much lower than previously reported in the literature but was about twice those of grasses and cereals, 0.05 to 0.1%. This evidence was of indirect nature and suggested a higher Ca requirement for legumes than for cereals and grasses. Direct evidence would require that legumes suffer Ca deficiency at concentrations which are adequate for cereals and grasses. In the soil, Ca requirement is influenced by many other factors. Loneragan (218) recorded large variations in the Ca requirement of 29 plants by varying the conditions of Ca supply.

Differences in sensitivity to Ca deficiency between tropical and temperate legumes appear to be related to a greater ability of tropical legumes to extract their Ca requirement from the soil rather than to differences in nutrient requirements (15, 265). The classical study on this subject was that by Andrew and Norris (15) conducted on an acid humic gley soil from the coastal lowlands of subtropical Queensland, Australia. These authors compared responses to Ca of five tropical and four temperate pasture legumes growing on a soil containing 0.1 meq Ca/100 g, or 3% Ca saturation. They found that the four temperate legumes (Medicago tribuloides Desr., Medicago sativa L., Trifolium fragiferum L., and T. repens) showed visual symptoms of Ca deficiency and their respective yields on the unlimed soil were 0.2, 1.5, 2.0, and 6.5% of the maximum yields obtained with added lime. The five tropical legumes (Desmodium uncinatum (Jacq.) DC., Indigofera spicata Forsk., Centrosema, Stylosanthes bojerii Vog., and Phaseolus lathyroides L.) did not show any visual symptoms of Ca deficiency and their respective yields on the unlimed soil were 25, 40, 52, and 68% of their maximum yield. All legumes produced maximum yields from approximately the same level of lime (600 to 800 kg/ha). The percentage Ca concentration in the tropical species was approximately equal to those in the temperate species. The authors postulated that the superior ability of the tropical species to grow and nodulate at low Ca levels was primarily related to their superior ability to extract Ca from the soil. In this respect, Medicago sativa, among the temperate species, was a highly inefficient species. At the other end of the scale, T. repens was the most efficient of the temperate species studied. In the tropical group, Desmodium uncinatum was the least efficient, but it was slightly better than T. repens. Stylosanthes bojerii was the most efficient of the tropical species. These legumes evidently fall into two groups which overlap at the Desmodium uncinatum-T. repens level.

Other investigators have reported on the differential response to lime among legumes. Russell (315) obtained significant yield increases to lime by T. repens but not by P. lathyroides on a Ca deficient solodic soil in Australia. The same author (315) also noted great variation in degree of response to lime among 48 species and strains of temperate legumes growing on the same soil. Jones and Freitas (200) found, in greenhouse studies with an Ultisol in Brazil, that Stylosanthes gracilis produced maximum yields at a lime rate of 625 kg/ha, but Centrosema, Glycine javanica, and Siratro reached maximum growth at a lime rate of 2,500 kg/ha.

Norris (265) proposed an interesting hypothesis to explain the observed difference in Ca absorption efficiency between tropical and temperate legumes. This author explained that the Leguminosae order originated in Upper Cretaceous times. The early Leguminosae evolved in a typical tropical environment; that is, the soils were very acid, deficient in P, leached to a very low exchangeable base content. At that time these conditions prevailed over a wider area of earth than the tropics occupy now. Changes that occurred during post-Cretaceous times caused the tropical zone to be restricted to its present boundaries. Two subdivisions of Leguminosae, families Mimosaceae and Caesalpinaceae, did not adapt to these changes and are restricted to the tropics and subtropics. The family Papilionaceae, on the other hand, produced a great number of genera and species that became adapted to the new conditions and occupied the temperate regions of the earth. Two tribes of the Papilionaceae, the Trifolieae and Vicieae, became adapted to high fertility soils and a calcicolic habitat. These two tribes constitute only 8% of the species in the Leguminosae, the remaining species have retained the characteristics of their ancestors, growing well on soils of low nutrient status commonly found in tropical regions.

Soil P Availability

Soil reaction and P availability.--In 1935, Pettinger (282) published a generalized chart relating soil pH to the availability of seven plant nutrients. In 1946, Truog (361, 362) improved this chart with the inclusion of 11 nutrients. According to Truog (361, 362) a pH range of 6.5 to 7.5 provided the most favorable conditions for P availability. This was one of the most important reasons cited for liming soils to pH 6.5. The belief was that at this pH a considerable amount of P in the soil existed as Ca phosphate, which was considered relatively soluble to H_2CO_3, and thus more available to crops. Lucas and Davies (225) published a similar chart for organic soils. In this chart, the favorable pH range for P availability fell 1 to 1.5 pH units lower than that indicated by Truog (361) for mineral soils.

Definition of soil P availability.--In this review of literature, P availability is defined to be a measure of the capacity of the soil to supply P for plant growth. Therefore, although an increase in P availability should cause an increase in total P uptake by plants, the inverse is not necessarily true; increased total P uptake by a plant is not conclusive evidence of increased P availability. This is so because liming may have indirect effects on total P uptake. On acid soils, lime can increase crop response to P fertilization by alleviating adverse soil conditions such as Ca and Mo deficiencies, or Al and Mn toxicities. For example, Rai, Prasad, and Mandal (292) and Mandall et al. (228) reported increased P uptake by several crops after application of lime to acidic, Ca deficient, red-loam soils in India. However, this effect could be attributed to increased Ca supply to the plants. Similar reports on the effect of lime on P uptake from Ca deficient soils are often found in the literature (39, 81, 180, 219, 315).

Some investigators (1, 190, 252, 259, 313) have also reported increased P uptake by crops after liming soils containing toxic levels of Al and Mn. These reports are more difficult to interpret in terms of P availability. In acid soils, Al can reduce growth by increasing P fixation and by toxicity of the Al ion. Both effects lead to a higher plant requirement for fertilizer P and a positive response to liming.

Negative effects of liming on P availability.--Barrow (30) reported from Australia that yields of two strains of subterranean clover (Trifolium subterraneum L.) were significantly depressed after liming an acid sandy Spodosol. The plants showed symptoms of P deficiency. Lime rates used in that experiment were approximately 0, 1,250, 2,400, and 10,000 kg/ha of $CaCO_3$. The first level of lime produced small increases in dry matter but higher lime rates decreased yields. The detrimental effect of liming was more marked at the lowest P level and highest lime level. With increasing rates of P application, the depressing effect of lime on yields decreased. The author (30) indicated that waterlogging eliminated the detrimental effect of liming. The soil was waterlogged in the greenhouse by adding water until there were a few millimeters of water standing on top of the soil. The moisture regime was maintained by daily additions of water. Barrow (30) indicated that the results suggested that lime decreased P availability, but this effect was opposed by P fertilization or increased P availability due to waterlogging. The increase in P availability in flooded soils is well known from rice cultivation (328). Under anaerobic conditions ferric phosphate is reduced to a more soluble ferrous form (255). Also, anaerobic bacteria produce H_2S enhancing the solubility of soil phosphates (255).

Sorteberg and Dev (338) studied the effect of four P levels and three lime rates on oats (Avena sativa L.) growing on three acid Norwegian organic soils. Lime rates ranging from 3,000 to 18,000 kg/ha depressed dry-matter yields and P concentrations in plant tops. There was no significant response to P fertilization on unlimed soils except for a negative response to the highest P rate. However, plant response to P increased with increased lime rates suggesting a negative effect of lime on P availability. Similar results suggesting negative effects of lime on yields and P availability have been reported by Lawton and Davies (212), Okruzko, Warren, and Wilcox (271), and Pierre and Browning (284).

Lime can affect P availability in soils by influencing P fixation, organic P mineralization, and inorganic P solubility through microbial action. Perhaps the best way to study the effect of lime on P availability is to deal with each one of these effects separately.

Phosphorus fixation.--The formation of crystalline phosphates has been proposed as one of the main mechanisms by which applied P is fixed in soils (84, 205, 206, 207, 313, 353). Several investigators (138, 151, 182, 273, 299) have postulated that adsorbed P may be equally important in the retention of P in soils. Liming can affect the solubility of crystalline phosphates or the nature of the adsorbing surface and consequently alter the concentration of phosphate in the soil solution.

Lindsay and Moreno (215) made a theoretical study of phosphate equilibria in soils at various pH values. They considered the solubilities and dissociation product constants of several P compounds that are expected to be present in soils, or which can be formed upon addition of P or lime. The relationship between phosphate in solution and pH was calculated through the use of the negative logarithm of the activity of $H_2PO_4^-$, pH_2PO_4. The assumption was made that the activity of Al, Fe, and F ions was determined by the solubilities of $Al(OH)_3$ (gibbsite), FeOOH (goethite), and CaF_2 (fluorite), respectively. The authors (215) predicted from these theoretical considerations an increase in phosphate concentration in solution by liming acid soils. The same analytical approach used by Lindsay and Moreno (215) was used by Molina[1] with six Costa Rican soils. He found increased solubility of soil phosphate, as evidenced by a decreased phosphate potential in water extracts, after addition of lime to the soils. Phosphate potential, $pH_2PO_4 + 0.5pCa$, is the negative logarithm of the activity of $Ca(H_2PO_4)_2$ in solution and its magnitude is inversely related to phosphate concentration in solution (313). On the other hand, some investigators (111, 352) have found that liming had no significant effect on the equilibrium phosphate concentration in the soil solution or in water extracts.

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[1] Molina, R., 1969. Efecto del encalado sobre las formas y disponibilidad del fosforo en seis suelos de Costa Rica. MSA thesis, Instituto Interamericano de Ciencias Agricolas, Turrialba, Costa Rica.

A shortcoming of studies such as that by Lindsay and Moreno (215) is that the assumption was made that the activity of the Al ion was determined by the solubility product of gibbsite. According to Hsu and Bates (183), polymerization of hydroxy-Al ions prevents the formation of gibbsite in soils until the pH is around 8. In addition, when P is added to acid soils, most of it has been reported to be in the Al-phosphate fraction (108, 129, 179, 226) according to the P-fractionation scheme of Chang and Jackson (73). A large proportion of phosphate in this fraction appears to be exchangeable with P32 (108), suggesting that the Al phosphate extracted contains a significant proportion of adsorbed phosphate (262). Therefore, adsorbed phosphate, probably on hydroxy-Al polymers, seems to be the most important material controlling phosphate concentration in solution (368).

Robertson, Neller, and Bartlett (307) studied the effect of lime and P applications on yields of oats and corn (Zea mays L.) growing on six acid Florida soils of various sesquioxide and residual P contents. Liming increased percent P in the plant from P32-tagged fertilizer when soils had high sesquioxide content but had no effect on soils with low sesquioxide content. These results suggested that lime increased P availability due to reduced P fixation in soils rich in sesquioxides.

Taylor and Gurney (352) indicated that liming five acid soils had little effect on the equilibrium phosphate concentration; however, the amount of phosphate extracted from the soil by an anion exchange resin increased significantly with increasing pH. Murrmann and Peech (262) indicated that the amount of labile phosphate in the soil and the concentration of phosphate in 0.01M $CaCl_2$ extracts reached minimum values at about pH 5.5 and increased as the pH varied from this value. Labile phosphate was determined by adding a known proportion of phosphate to the soil as P32. The added P32 underwent isotopic exchange with phosphate ions that dissociated from exchange surfaces. The results obtained by Taylor and Gurney (352) suggested that lime had no effect on the solubility of soil phosphate but probably decreased the energy of phosphate adsorption; this made the phosphate more easily removable by the anion-exchange resin. The findings by Murrmann and Peech (262) indicated that liming had an effect on both adsorption energy and phosphate concentration in solution.

Some investigators (23, 210, 330) have reported a positive effect of lime on chemically extractable P. On the other hand, Helyar and Anderson (166) found no effect of lime on $NaHCO_3$-extractable P in some infertile acid soils in Australia.

Reeve and Sumner (297) reported that liming eight Oxisols from South Africa had no effect on P fixation as measured by P-desorption isotherms. Fassbender and Igue (121) obtained similar results with a limed Costa Rican Andept. Molina[2] found that lime had no significant effect on P fixation by two Andepts and two Oxisols in Costa Rica; however, this author indicated that one Entisol showed increased P fixation with increased liming rates. Fox, Dedatta, and Wang (131) reported decreased P retention in Hawaiian soils after liming; minimum P retention occurred at pH 5.0 to 6.0. One factor that affects the interpretation of some of these investigations is that when soils are limed, even if finely ground material is used, a fraction of the added lime may not react (24, 46, 297). Any decrease in P extracted from limed soils may be due to a weakening of the acid extractant by the unreacted lime (24, 297).

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[2] Molina, R., 1969. Efecto del encalado sobre las formas y disponibilidad del fosforo en seis suelos de Costa Rica. MSA thesis, Instituto Interamericano de Ciencias Agricolas, Turrialba, Costa Rica.

The effect of lime on the availability of applied P may differ from its effect on the availability of soil native P. Sillanpaa (330) reported that lime increased Chang and Jackson's water-soluble P after P fertilization but had no effect on the solubility of native soil P. Similar results from six acid Florida soils were reported by Robertson et al. (307).

Lime may increase the dissolution of crystalline phosphate compounds in soils (215). In most acid soils, however, and particularly in tropical soils with high content of active Fe and Al sesquioxides, the effect of lime is probably primarily on the phosphate adsorption mechanism. This effect may result in changes in adsorption energy (352), which may be reflected in the phosphate concentration in the soil solution (262).

Phosphorus mineralization.--Although there is a wide variation in the organic P content of soils, this fraction averages 50% of the total P in mineral soils (189, 211). The C/P ratio in mineral soils (100 to 200) is generally lower than that of organic soils (200 to

1,900). Cultivated soils generally exhibit lower C/P ratios than uncultivated soils (255). These relations between organic C and P in soils suggest that organic P is more resistant to microbial decomposition than organic C.

Dyer and Wrenshall (110) claimed that acid soils usually contain a smaller proportion of organic P than neutral soils. This contention is supported by data collected by Fassbender, Muller, and Balerdi (122). These authors found that in 107 Central American soils the organic P content averaged 50% of the total P in neutral or slightly acid soils dominated by Ca phosphates, and 41% in acid soils with predominantly Fe and Al phosphates.

Soil reaction has a marked influence on the relative proportions of microorganisms existing in soils (8, 43). Soil pH also has a determining effect on the rate of decomposition of soil organic matter (30, 158, 379, 383).

MacLean and Cook (227) indicated that lime markedly increased the supply of available P in some acid Canadian Spodosols. Halstead, Lapensee, and Ivarson (152) presented evidence of enhanced mineralization of organic P after liming soils similar to those used by MacLean and Cook (227). These authors (152) also reported that lime markedly increased microbiological activity, as indicated by increased CO_2 and NO_3-N production. Awan (23) obtained significant yield increased by liming two acid soils; pH 5.5, from El Zamorano, Honduras. He observed increased extractable-P and decreased organic P values after liming. He postulated that liming liberated P from the soil organic fraction and increased plant growth. Other investigators (144, 152, 238, 278) have reported similar effects of lime on P mineralization.

in acid soils. Sometimes the amounts of P mineralized during a growing season have been reported to be rather small, in the order of a few ppm (144).

Immobilization of inorganic P may occur in soils with relatively large contents of C and N and low levels of inorganic P; this may occur in soils with C/P ratios greater than 200 (8, 43, 313). In early stages of decomposition, a considerable amount of organic P is synthesized by microorganisms at the expense of the inorganic P fraction, reducing temporarily the availability of this element in the soil. As decomposition progresses, organic P is gradually mineralized and released into the soil in a more available inorganic form (8, 43, 72, 313).

In acid soils, phytin plays an important role as reservoir of organic P. Phytin is a Ca or Mg salt of phytic acid, six molecules of H_3PO_4 with inositol as inositol hexaphosphate (313). Phytin and related compounds can constitute from 25 to 90% of the soil organic P (8).

Heck and Whiting (164) found that phytin was quite available to oats in sand culture. Rogers, Pearson, and Pierre (310) indicated that phytin and lecithin could be absorbed directly from the nutrient solution by corn and tomato. The rate of absorption of phytin was similar to that of inorganic orthophosphate. Bertramson and Stephenson (37) found that, in contrast to results obtained in sand culture, phytin was not utilized to any extent by tomatoes in acid soils. Wrenshall and Dyer (386) pointed out that in acid soils phytin forms insoluble salts with Fe and Al. In alkaline soils, phytin reacts to form salts with Ca. Wrenshall and Dyer (386) indicated that Fe and

Al phytates were resistant to dephosphorylation by the enzyme phytase in acid solutions. Conrad (96) reported that phytin has a low availability in soils with a pH below 6. It appears that Fe and Al phytates in acid soils are less soluble than the inorganic P salts of these metals (255).

Phytin has also been reported to be adsorbed strongly by clay minerals (147). Goring and Bartholomew (147) reported that adsorption of phytin by bentonite was highly pH dependent. The adsorption was strongest at pH 3.5 to 4.5. At pH values above 6.5 the strength of adsorption decreased rapidly. These authors (147) also indicated that nucleic acids were adsorbed in a similar way at low pH.

Nucleic acids are also available to plants through direct uptake or mineralization (37). Pearson, Norman, and Ho (278) reported that 60 to 85% of yeast nucleic acid was dephosphorylated within 60 days after addition to Iowa soils. Bower (48) indicated that pH can influence nucleic acid dephosphorylation. In soils with pH 5.5 or higher, 75 to 80% of nucleic acids added to Iowa soils were dephosphorylated. In more acid soils, only about 50% of nucleic acid P was released.

One possible reason for the lower rate of breakdown of nucleic acids in acid soils could be increased adsorption on acid clays. Bower (49) studied the adsorption of nucleic acids and guanine nucleotide by kaolinite and bentonite at various pH values. The extent of adsorption of these P compounds by clay minerals increased asymptotically with increased pH. Adsorption of nucleic acids by bentonite was nil at pH 6.5. However, 30 and 75% of nucleic acids added were adsorbed at pH 5 and 4.5, respectively. Both nucleic acids and guanine nucleotide were adsorbed more by bentonite than by kaolinite.

Phosphate-dissolving microorganisms.--Gerretsen (143) demonstrated that microorganisms enhanced the solubility of inorganic P. Many soil microorganisms produce organic acids such as formic, acetic, lactic, citric, and succinic which are capable of dissolving $Ca_3(PO_4)_2$ and several forms of apatite (343,348). Some investigators (107, 342) have indicated that alpha-ketogluconic acid and other alpha-hydroxy acids are very effective chelating agents for metals such as Ca, Cu, Ni, Mn, Fe, and Al. In acid soils, with predominance of Fe and Al phosphates, such chelating organic acids would increase the availability of soil P.

Phosphate-dissolving microorganisms are common in soils. Stevenson (343) indicated that they can constitute 10 to 15% of the microbial population in the soil, and 20 to 40% in the plant rhizosphere. These microorganisms have relatively large requirements for high energy compounds (190). Rovira (312) claimed that the nature of root exudates exerts a great influence on microbial activity in the rhizosphere, and consequently on nutrient availability.

Other types of bacteria have been reported to be able to utilize ferrous and ferric phosphates, producing FeS and H_3PO_4 as end products (348).

There is no conclusive evidence in the literature concerning the relative importance of phosphate-dissolving microorganisms under field conditions (257). Calcium carbonate, or other buffering agents, could be expected to neutralize the acids produced and reduce their phosphate-solubilizing effect.

Aluminum Toxicity

Symptoms.--Some visual symptoms frequently associated with Al toxicity are: inhibition of main root elongation and branching; main roots become thick and distorted, and lateral roots remain as short stubs. Roots are usually affected before shoots. At low Al concentrations, roots may be affected but not the tops. Tops generally exhibit symptoms resembling severe P deficiency, particularly the deeper green and reddish coloration (190, 259).

Aluminum in exchangeable form.--Many investigators (111, 133, 134, 190, 202, 306) have indicated that Al toxicity is the most common cause of acid soil infertility. Coleman, Kamprath, and Weed (88) and Kamprath (202) have recommended liming acid soils primarily to neutralize the exchangeable Al present. In studies conducted in North Carolina with four acid Ultisols, Kamprath (202) found that 900 to 4,200 kg/ha of $CaCO_3$ reduced Al saturation to less than 30%. This author indicated that growth of corn was not affected when Al saturation in the soil was less than 44%, 0.22 to 1.6 meq Al/100 g. Soybeans (Glycine max L. (Merr.) and cotton appeared to be more sensitive to Al toxicity and required Al-saturation values below 20%, 0.87 to 3.5 meq/100 g, for optimum growth. Other authors (252, 297), have obtained good correlations in Oxisols and Ultisols between yields and exchangeable-Al values down to 0.05 to 0.10 meq/100 g soil. Nye et al. (270) indicated that Al is not found in appreciable amounts in the soil solution until Al saturation reaches approximately 60%. This would indicate that percentage Al saturation should be used to define toxic levels of Al in the soil.

Aluminum in solution.--The effect of Al toxicity on plant growth has been generally studied in solution cultures. Aluminum levels toxic to plants in solution are commonly found in acid soils (190), suggesting that Al toxicity may be a responsible factor for acid soil infertility. In field studies, the evidence for Al toxicity is mostly indirect in nature, generally consisting of correlations between plant growth and levels of exchangeable or extractable Al in soils. One of the few exceptions was the work conducted by Vlamis (370). This author presented definite evidence that Al toxicity was responsible for poor plant growth in an acid soil and was not related to other confounding factors.

It may be appropiate to indicate at this point that Al has also been reported to have a beneficial effect on growth of some plants. Chenery (78) reviewed this subject and concluded that tea (Camellia sinensis (L.) O. Kuntze), which accumulates as much as 40,000 ppm of Al in the dry matter, definitely requires this element. Hortenstine and Fiskell (181) reported that root growth of sunflowers was increased slightly by 1 ppm of Al in solution. Growth of some plant species can be markedly decreased by 1 ppm Al in solution. The toxicity of a given concentration of Al can be greatly influenced by the presence of other ions. It also varies with plant species and even varieties, and stage of plant development. For example, Munns (259) indicated that Trifolium subterraneum showed only slight Al toxicity symptoms in solution culture containing 5.4 ppm of Al, but Medicago sativa failed to grow at the same Al concentration. Similar results were reported by Helyar and Anderson (166). Vidal and Broyer (365) showed that 4 to 17 ppm Al in solution was toxic to corn when Mg was 10^{-4}M but not when it was 10^{-3}M.

Aluminum mobility in plants.--The mobility of the Al ion in plants is low (190). For example, some investigators (132, 285) have reported that additions of Al to culture solutions resulted in marked increases in Al content of roots but little in shoots. At the physiological pH of root tissues, Al would be expected to form insoluble Al hydroxides and phosphates (190). However, the cell environment may alter the solubility of the Al compounds formed. Some plants, notably the tea plant, can translocate and accumulate Al in the above-ground tissue (78). Chenery (78) pointed out that Al-accumulating plants had very acid cell saps, pH 4.3 to 4.8. In these plants, normal metabolic processes do not seem to be affected by the high amounts of Al present (78).

The ability of organic molecules, particularly organic acids, to complex Al may contribute to the differential response of plants to high Al levels in their tissues (190). Jones (198) found that root macerates of barley (Hordeum vulgare L.), and peas (Pisum sativum L.) were able to complex Al strongly. Jackson (190) hypothesized that the mobile form of Al is an organic acid complex and that Al in this form is not able to precipitate P, thereby alleviating the toxicity. Correlations between yields and Al concentrations in shoots under Al toxicity conditions, which would test this hypothesis, are almost nonexistent in the literature (190). Several authors (111, 259) have reported that Al toxicity could be alleviated by adding chelating agents, such as EDTA (ethylenediaminetetra acetic acid), to the solution culture. DeKock and Mitchell (104) showed that high levels of Al chelates were absorbed by tomatoes without Al toxicity symptoms.

Interaction with Ca, Mg, and K.--Aluminum has been reported to markedly decrease Ca concentrations in the tops of several plants

(295). Other workers (259, 320) have reported restricted translocation of Ca from roots to shoots induced by Al. Harward et al. (161) found that the distribution of Ca in the plant was affected by Al. He indicated that Al decreased Ca concentrations in older leaves of lettuce but had no effect on young leaves.

Aluminum toxicity inhibits root elongation and formation of lateral roots (172). Lack of Ca and P are also known to inhibit root growth (172). However, the pattern of root inhibition observed in cases of Al toxicity is unlike that induced by P deficiency (190). For example, Al does not inhibit lateral root initiation but does restrict its subsequent development which produces the stub-like appearance of roots generally associated with Al toxicity (190). On the other hand, in cases of P deficiency lateral root initiation is restricted (172, 190). Root symptoms of Al toxicity are more like those induced by Ca deficiency in that lateral-root primordia develop but most of them do not grow further (172). In addition, binucleate cells in the root tissue are characteristic of Ca deficiency and they have also been reported in root tissue damaged by Al (190). However, Ca deficiency affects division and elongation of root cells whereas Al appears to restrict cell division (172, 190). Jackson (190) pointed out that although Ca uptake is strongly inhibited by Al, overcoming Al toxicity in solution cultures by increasing Ca concentration has been unsuccessful. Hallsworth, Greenwood, and Audon (149) obtained some alleviating effect by adding Ca at low Al levels but not at concentrations of 10 to 20 ppm Al.

High levels of Al have been reported to decrease Mg and K concentrations in the tops of some plants (161, 295). However, the relationships between Al and Ca, Mg, K, and other ions is complicated by antagonistic and synergestic effects often observed among these ionic species. Unless a mechanistic model is available to explain different interactions among these metals, a mere enumeration of effects is useless and very confusing

Interaction with P.--Aluminum toxicity symptoms have often been reported to resemble P deficiency symptoms (133, 258, 285). Pierre and Stuart (285) indicated that addition of P alleviated Al toxicity symptoms in some acid soils and greatly increased plant growth although Al concentration in the soil solution was found to be within toxic levels. These authors (285) supplied plants in solution culture with P and Al in alternate days in order to prevent Al precipitation in the solution. They found that increased P levels decreased toxicity although plant concentration of Al was not affected significantly. On the other hand, Munns (258) reported that Al toxicity was not remedied by increasing P supply in solution although P concentration in plants was increased to 0.45%; the toxicity was alleviated only when P was added at rates high enough to precipitate Al in solution.

Some authors (43, 190, 258, 313) have reported accumulation of P in roots of plants growing in media high in Al. This has generally been reported to be associated with reduced transport of P to shoots. However, Munns (258) found P accumulation in roots of *Trifolium subterraneum* but not of *Medicago sativa*. Randall and Vose (293) stated that increased P accumulation in roots is not essential for inhibition of growth by Al. On the other hand, several investigators (86, 387) have shown that Al phosphate precipitation occurs in some plant roots internally as well as on epidermal cell surfaces.

Foy and Brown (133) reported that tolerance to Al by several plant species was closely correlated with ability to absorb and utilize P in the presence of excess Al. Jones (198) hypothesized that organic acids produced by plant roots chelated Al preventing the precipitation of Al phosphates. In support of this hypothesis, Foy and Brown (133) reported that chelated Al in solution did not affect plant growth of P uptake at the same concentration that unchelated Al did.

The evidence in the literature indicates a negative effect of Al, particularly at high concentrations, on the uptake of other metallic cations such as Zn, Cu, and Fe (44, 172, 173, 190, 295). As mentioned earlier, some investigators (190, 198) postulated that the mobile form of Al in plants is an organic acid complex. Although there is no reference to this in the literature, this theory could also provide a mechanism for the observed effects of Al on Mn, Cu, Zn, and Fe uptake and transport. All these metals can form complexes with organic molecules (99). Assuming that their mobility or utilization depend on complex formation, competition for complexing sites would result in antagonistic interactions. An increase in concentration, particularly of the more efficient complexing metals, would decrease the mobility of other cations, thereby reducing their concentrations in plant tops. Investigations concerning the activities of Cu, Co, Ni, Mn, Cr, Zn, Cd, and other metals in inducing Fe chlorosis seem to support this hypothesis. Hewitt (172) indicated that their relative activities followed the order of stability of metal-organic compounds. He stated that the relative stability of metal-organic complexes is almost independent of the ligand and generally decreases in the series: Cu^{2+}, Ni^{2+}, Fe^{3+}, Zn^{2+}, Cd^{2+}, Fe^{2+}, Mn^{2+}, and Mg^{2+}.

The plant internal system is so complex, however, that so far it has been difficult to determine if the effects of Al on the uptake of other ions is direct or if secondary effects are involved.

Manganese Toxicity

Symptoms.--Hewitt (172) stated that the effect of Mn toxicity in plants can occur in at least two ways: Mn-induced Fe chlorosis, and a direct effect of the Mn ion. Manganese-induced Fe chlorosis symptoms are similar to Fe deficiency symptoms. The circumstances under which this type of toxicity occurs have been extensively investigated (172).

Symptoms of Mn toxicity have been described by Hewitt (172) for a number of plants and are variable depending on plant species and degree of toxicity. In general, roots take on a brownish coloration; older leaves show a mottled appearance. In some cases, dark-brown or dark necrotic areas appear along petioles and leaf veins. It is possible that these dark areas contain large accumulations of Mn but the evidence is not conclusive (172). There is often a white or yellow-green chlorosis of the leaf margin. Some plants show pronounced marginal cupping of the leaves due to restricted marginal growth.

Soil analysis indexes of Mn toxicity.--Manganese occurs in nature in various positive states of oxidation, namely: 7, 6, 4, 3, 2 (2, 99). Only the 4, 3, and 2 states are important in soils (2). This element can be found in soils mainly in five forms: In the clay mineral structure, insoluble oxides of trivalent and tetravalent Mn, exchangeable divalent Mn, organic matter complexed Mn, and divalent

Mn in the soil solution (2, 248). The immediate source of plant-available Mn is in the soil solution, which is in equilibrium with exchangeable Mn and Mn oxides (2). The relative contribution of these two Mn forms to that in the soil solution is determined by soil reaction (2, 313). The solubility of Mn oxides, and consequently the Mn concentration in the soil solution, increases markedly with degree of acidity (59). At very low pH values, the Mn concentration in the soil solution may reach toxic levels (4, 139). However, increasing organic matter content and degree of soil aeration can reduce the amount of plant-available Mn through complex formation and microbiological oxidation (248, 255).

Adams (2) indicated that the best estimate of available Mn in soils with pH above 5.5 is the content of exchangeable Mn. However, in acid soils, pH below 5, probably the best availability index is the content of water-soluble Mn. This is based on the assumption that in acid soils the content of Mn in the soil solution is determined primarily by the solubilities of the Mn oxides. On the contrary, at high pH values, the oxides are relatively insoluble and the concentration of Mn in solution is controlled by the exchangeable fraction. Morris (251) found no overall relationship between exchangeable Mn and soil pH; for a specific soil, however, changing the pH by additions of $CaSO_4$ or $CaCO_3$ produced changes in water-soluble Mn and plant uptake. Fergus (123) indicated that exchangeable-Mn values were of little benefit for predicting Mn toxicity. He suggested that Mn toxicity should be suspected in soils of low pH and high content of easily reducible Mn.

In solution cultures, the concentration of Mn necessary to induce toxicity symptoms varies with plant species and the ionic environment of the solution. For example, Olsen (272) found that 1 to 4 ppm of Mn in solution depressed yields of soybeans and barley, but corn tolerated 15 ppm without a yield depression. Wallace, Hewitt, and Nicholas (375) showed that foliar symptoms associated with poor growth of plants on acid soils in England could be reproduced by growing plants in sand culture containing 12 to 25 ppm of Mn.

Role of microbiological processes in Mn toxicity.--Plants absorb Mn in the divalent state, or manganous form (43). The higher oxidation Mn ions form relatively insoluble oxides (59). Therefore, conditions favoring oxidation of divalent Mn can reduce its availability to plants. The oxidation of divalent Mn in the absence of microorganisms does not generally occur unless the pH is higher than 9 (255). However, specific Mn-oxidizing microorganisms are able to oxidize Mn, probably to MnO_2, even at pH values below 6 (60). These specific Mn oxidizers include bacteria as well as fungi and yeast (255). A number of nonspecific microorganisms have also been reported to oxidize Mn in agar cultures at pH values between 7 and 8. These microorganisms oxidize Mn in the presence of hydroxyacids such as citric, malic, or latic, which are common microbial metabolites (255). The relationship between Mn oxidizers and other soil microorganisms can be very complex as illustrated by experiments conducted by Bromfield (60) and Zavarzin (391). The latter found that the bacterium Metallogenium oxidized Mn only in the presence of a living fungi. Bromfield (60) reported that Corynebacterium oxidized Mn only when living in association with a Flavobacterium or a Chromobacterium.

There is no conclusive evidence concerning the importance of microbiological Mn oxidation under field conditions. Quastel (290) reported that when Mn was perfused through a slightly alkaline soil, the rate of Mn oxidation increased rapidly after a lag period. Soil sterilization or addition of metabolic poisons inhibited Mn oxidation. Gerretsen (142) found that oat plants growing in sterile sand culture suffered Mn deficiency only when the cultures had been inoculated with some Mn deficient soil.

In acid soils, pH below 5.5, particularly those high in organic matter, the formation of metallo-organic complexes is believed to be the main mechanism by which Mn is made unavailable to plants after liming (165, 275).

Toxic levels in plant tissues.--Manganese concentrations in plants vary greatly when Mn toxicity symptoms first appear. Manganese concentrations in plant tops of several species when dry-matter yields were significantly depressed by excess Mn are shown in Table 1. Although these Mn toxicity threshold values were obtained under quite variable environmental conditions, they illustrate the general range of Mn concentrations to be expected in plant tops under toxicity conditions.

Plant sensitivity variations.--Andrew and Hegarty (14) compared the response of several tropical and temperate pasture legumes to excess Mn in water culture. These authors found that tropical species did not differ significantly from temperate species in susceptibility to Mn excess; within each group, however, there were varying degrees of tolerance. *Centrosema* and *Lotononis bainesii* Baker were the most tolerant of the 12 species studied, growing relatively unaffected in solutions containing less than 20 ppm of Mn. *Trifolium repens* was

Table 1. Manganese toxicity threshold concentrations in oven-dry herbage of some plant species.

Plant species	Threshold value Herbage Mn, ppm	Reference	
	Tropical pasture legumes		
Centrosema pubescens	1,600	Andrew and Hegarty (14)	
Stylosanthes humilis	1,140	"	"
Lotononis bainesii	1,320	"	"
Phaseolus lathyroides	840	"	"
Leucaena leucocephala	+550	"	"
Desmodium uncinatum	1,160	"	"
Glycine javanica	560	"	"
Phaseolus atropurpureus	810	"	"
	Temperate pasture legumes		
Trifolium repens	650	"	"
Medicago sativa	380	"	"
Trifolium fragiferum	510	"	"
Medicago truncatula	560	"	"
	Other crops		
Phaseolus vulgaris	1,000	Lohnis (217)	
	1,000	Fergus (123)	
Hordeum vulgare	100	Vlamis and Williams (371)	
	1,000	Fergus (123)	
Solanum tuberosum	1,000	Lohnis (217)	

also relatively tolerant to Mn excess; it grew well in solutions containing less than 15 ppm of Mn. *Stylosanthes humilis*, *P. lathyroides*, *Desmodium uncinatum*, and *Trifolium fragiferum* were significantly affected by concentrations higher than 10 ppm. The most susceptible species were *Leucaena leucocephala* (Lam.) de Wit, *Glycine javanica*, *Medicago sativa*, *Medicago truncatula*, and Siratro, with critical values between 3.5 and 7 ppm of Mn in solution. It is interesting to note the lack of correlation between tolerance to Mn excess and Mn toxicity threshold values. *Centrosema* and *Lotononis bainesii*, the two most tolerant species, had relatively high threshold concentrations (Table 1); however, Siratro, the most susceptible species, had also a relatively high content of Mn in the tissue. On the other hand, *T. repens* had a relatively low threshold value but was one of the most tolerant species.

Souto and Dobereiner (340) reported that *Centrosema* and Siratro were the only species that nodulated when grown on a Brazilian Spodosol to which 50 ppm of Mn had been added. The remaining species (*Glycine javanica* vars. SP-1 and Tinaroo, and *Stylosanthes gracilis*) failed to nodulate. These authors indicated that the variety SP-1 of *Glycine javanica* was more tolerant to excess Mn than the variety Tinaroo. Freitas and Pratt (137) reported that Siratro seemed to be highly sensitive to Mn toxicity in some Brazilian acid soils; this was in agreement with results obtained in culture solutions by Andrew and Hegarty (14).

The differential tolerance to Mn toxicity observed among plant species grown in culture solutions can be magnified further in the soil by the plant rhizosphere and associated microorganisms. For example, Timonin (357) showed that the rhizosphere of an oat variety susceptible to Mn deficiency contained a greater number of Mn-oxidizing bacteria than the rhizosphere of another resistant variety.

Interaction with other plant nutrients.--The absorption, transport, utilization, and distribution of Mn in plants are influenced greatly by the presence of other nutrients in the growing media.

Manganese absorption by plants in culture solutions is reduced by high H ion concentrations (117, 371); this is also true for other metallic cations such as Ca, Mg, Fe, Zn, and Cu (117). In acid soils, this effect is opposed by the decreased solubilities of the Mn oxides (59); therefore, the net effect is usually one of decreased Mn uptake with increased pH (190).

Swanback (349) found that application of Ca decreased Mn concentrations in tobacco (Nicotiana tabarum L.) leaves more than in roots, suggesting a negative effect of Ca on Mn translocation from roots to shoots. Andrew and Hegarty (14) and Ouellette and Dessureaux (274) postulated that the relative tolerance of plant species to Mn toxicity may be related somehow to the retention of Mn within the root system. Wallace et al. (375) indicated that Mn injury to plants in culture solution could be alleviated by increasing the Ca concentration.

Munns, Jacobson, and Johnson (261) reported that there were at least three definable Mn fractions in roots of oat plants. One fraction was readily extracted with a salt solution. The other two fractions differed in the rate at which they reached isotopic equilibrium with an external Mn solution, and in the rate of transport from roots to tops. Jackson (190) hypothesized that Ca may affect the mobility or the relative proportion of the labile-Mn fraction.

Vlamis and Williams (371) indicated that Mg was more effective than Ca in reducing Mn uptake by barley when nitrate and sulfate salts were used; however, the opposite was true with phosphate salts. Lohnis (217) found that the negative effect of Ca and Mg on Mn uptake in solution culture was more evident with beans (Phaseolus vulgaris L.) and potato (Solanum tuberasum L.) than with some brassica crops, and was not observed with Medicago sativa.

Swanback (349) reported that increased K supply resulted in increased Mn concentrations in roots and tops; however, Mn concentration in plant tops continued to increase beyond that K level at which increases in root Mn ceased. These results suggested an effect of K on absorption and transport of Mn from roots to tops.

Hewitt (172) indicated that tolerance to excess Mn generally increased in the series: brassica crops, barley, potato, oat, and sugar beet (Seta vulgaris L.). The reverse order was indicated for increasing tolerance to Al excess. Jackson (190) explained that large additions of Mn to solutions containing Al would increase growth of plants susceptible to Al toxicity.

Information on the effect of P on Mn absorption is scarce. The effect of P on Al uptake is believed to be greater than on Mn uptake (172). Under some conditions P may increase Mn uptake by its negative effect on Al uptake (190). This would be particularly noticeable at high P and Al concentrations where P reduces Al activity by precipitation.

The antagonistic interaction between Mn and Fe has been studied extensively. One form of Mn toxicity is Mn-induced Fe chlorosis. It has been shown that Co, Zn, Ni, Cu, Mo, Cr, and particularly Cd are also active in inducing Fe deficiency (172). The hypothesis of metallo-organic complex formation has been suggested as an explanation for metal-induced Fe chlorosis (169, 170). This hypothesis can also be useful in explaining the interaction between Mn and other heavy metals.

Taper and Leach (351) reported that increased Ca supply in solution decreased the uptake of Fe and Mn by Phaseolus vulgaris. At the same time, increased Fe supply decreased Mn uptake. The negative effect of Fe on Mn uptake was reduced with increased Cu supply. Somers and Shive (337) showed that increased Fe supply decreased Mn concentration in soybeans but had the opposite effect on the proportion of soluble Mn in plant tissue; these results suggested that Fe influenced total Mn in the plant and its chemical nature.

The report by Somers and Shive (337) illustrated the most serious limitation of studies concerning effects of nutritional parameters on plant nutrient uptake. By reporting total content of a given element in a particular plant tissue, the assumption is made that the element exists in the tissue in a homogeneous chemical form, or that different forms are not pertinent to the effect under study. This is not true in most cases. For example, work by Munns et al. (261) indicated that Mn in root tissue existed in at least three forms; each one with different mobilities and exchange properties. Until definable fractions for each element are established, the effect of one nutrient on the properties of another cannot be delineated precisely. This is complicated even further by the heterogeneous distribution of mineral elements among different plant parts, and the effect of the plant growth cycle on their distribution. The effect of environmental conditions is often disregarded; many reports have to be interpreted with caution because they contain an unknown number of uncontrolled experimental variables. Rorison, Sutton, and Hallsworth (311) showed that harmful effects of 50 ppm of Mn on the growth of Medicago sativa in solution culture were more drastic at high than at low light intensity.

Micronutrient Availability

Pettinger (282) in 1935 and Truog (361, 362) in 1946 and 1948 published generalized charts relating the availability of plant nutrients to soil pH. Since then, the relationship between soil reaction and micronutrients availability has become a well-established concept in soil science (43, 177, 313, 317). The availabilities of Mn, Cu, Zn, Fe, and B are greater in acid soils and are reduced by increasing soil pH. Molybdenum, on the other hand, is the only micronutrient that becomes more available with increasing pH (43, 177, 313). In general, the effect of pH on the availabilities of Mn, Mo, and B is greater than on Cu, Zn, and Fe (177). For example, Christensen, Toth, and Bear (82) incubated a soil high in total and exchangeable Mn; they found that liming the soil from pH 4.6 to 6.5 decreased the content of exchangeable Mn approximately by 95%. In contrast, other investigators have reported that the uptake of Cu (286) and Zn (71) by plants appear to be independent of soil pH. However, Fiskell (127) claimed that the method used to correct Cu toxicity in certain areas of Florida was by liming the soil to about pH 6.5 to 7. Adams and Pearson (3) cited several cases of Zn deficiency in the southeastern region of the United States aggravated by liming. Camp (71) postulated that the lack of correlation sometimes observed between plant uptake of Zn and soil pH may be related to the complexing effect of soil organic matter. A great deal of controversy could be clarified by considering the effect of pH on the mechanisms responsible for fixation of micronutrients in soils. The chemical form of an element in the soil is also an important factor in determining the effect of pH on its availability. For example, Beeson, Gray, and Hammer (35) found that liming had no effect on plant uptake of native Mn, Cu and Co but greatly reduced uptake of applied forms.

Formation of insoluble oxides.--This fixation mechanism is particularly important in relation to Mn availability; some aspects have already been discussed in reference to Mn toxicity. In summary, the conversion of divalent Mn to higher oxidationoxides reduces its availability (59). The oxidation of Mn in soils appears to occur primarily by biological means (63, 229). Mann and Quastel (229) found that some biological poisons inhibited the oxidation of Mn. The biological oxidation of Mn occurs either with direct or indirect participation of soil microorganisms (255). Some nonspecific Mn oxidizers can induce the oxidation of Mn in the presence of citrate by increasing the alkalinity of the medium through metabolic processes. Other microorganisms are capable of oxidizing Mn directly in the absence of citrate on soil-agar plates (358).

Some investigators (140, 184, 372) have studied the effect of organic matter additions on Mn availability. Wain, Silk, and Wills (372) found that Mn applied to calcareous soils became unavailable within a week; however, addition of organic matter made it possible for the plant to use the added Mn throughout the growing season.

Similar favorable effects of organic matter additions on Mn availability were reported by Fujimoto and Sherman (140) and Christensen et al. (82). Hurwitz (184), on the other hand, found no effect of added organic matter on exchangeable Mn in a sandy-loam soil. These apparently conflicting results appear to be related to the kind of organic matter used, and probably to conditions of oxygen supply during the experiment. Several microorganisms which decompose organic matter have been reported to use MnO_2 instead of oxygen as H^+ acceptor, resulting in the formation of divalent Mn (229). Manganese dioxide can also be reduced to manganous ions by certain compounds formed through microbiological processes under restricted oxygen supply (255).

Nonbiological oxidation of Mn does not take place unless the pH exceeds 9 (255). In the presence of hydroxyacids, oxidation of Mn has been shown to occur at pH values as low as 7 or 8. However, specific Mn-oxidizing microorganisms can oxidize Mn at pH values below 6 (255). Increasing pH promotes the biological oxidation of Mn and decreases the solubilities of the oxides formed.

Iron can also be immobilized by formation of insoluble oxides. Gleen (146) demonstrated that a $FeSO_4$ solution was oxidized upon passing through a soil column. The rate of oxidation followed a sigmoid-shaped curve, generally found in biological systems, and was inhibited by cell poisons such as azide and toluene. Hodgson (177) indicated that in most soils biological activity is not necessary to account for the formation of Fe oxides. Development of ferruginous nodules, however, can not be explained by nonbiological processes (177).

The oxidation of Fe and Mn can be reversed by impeded drainage (177). The reduction process is an energy-requiring reaction and can be promoted by additions of easily decomposable organic matter (294).

Soil reaction influences the oxidation of Fe and the solubilities of the oxides formed in a manner similar to that described for Mn. The ferrous ion has been reported to be more abundant in acid soils, pH less than 5, whereas the ferric form is favored above pH 6 (8).

Adsorption on silicate mineral surfaces.--There is some evidence that adsorption of Co, Cu, and Zn on mineral and organic surfaces involves forces in addition to Coulombic forces responsible for alkaline-alkali cation adsorption (176, 177). Some investigators (174, 279) reported that a fraction of Cu and Zn added to soils could not be recovered by NH_4OAc extraction. Peech (279) reported that retention of Zn against neutral-salt extraction was pH dependent. Brown (64) indicated that Zn could be recovered completely immediately after addition, but that the nonextractable fraction increased with time. Zende (392) reported similar fixation of Co added to soils.

Elgabaly and Jenny (112) reported that a portion of Zn added to montmorillonite could not be extracted with neutral salts. A large portion of nonexchangeable Zn was later found to be extractable with acid. However, even acid treatment could not remove a small fraction of the Zn added, which was assumed fixed in the crystal structure. Banerjee, Bray, and Melsted (26) reported that the CEC of soils and clays decreased by an amount equal to the nonexchangeable Co retained. These authors also demonstrated that the amount of nonexchangeable Co retained increased with increased pH. Subsequent work indicated that Cu is strongly bound to silicate mineral surfaces (177). Hodgson (177) indicated that adsorption of Co by montmorillonite is an endothermic reaction and can be eliminated by treatment with F ion. This author postulated that the Co-to-clay bond was through hydroxyl groups on mineral surfaces that are replaceable by F. DeMumbrum and Jackson (105) found that adsorption of Cu by montmorillonite affected the infrared peak associated with surface hydroxyl groups.

Several investigators (41, 163) have indicated that B can be adsorbed on clay mineral surfaces; B adsorption by soils has been described by the Langmuir adsorption isotherm (177). It has been suggested also that B can be fixed in the crystal lattice (153). Hodgson (177) stated that the evidence, although not conclusive, strongly suggests B entering the crystal structure.

Adsorption on sesquioxide surfaces.--Iron oxides generally are not precipitated in solution as individual particles but exist as surface coatings on silicate minerals (177). Jones (196, 197) has studied extensively the adsorption of Mo on Fe oxide surfaces. He indicated that hydrous Fe oxide adsorbed Mo more strongly than Al oxide, halloysite, nontronite, and kaolinite, in that order. Removal of Fe oxides markedly decreased Mo retention by the soil. Jones (197) also demonstrated that adsorption of Mo by Fe and Al oxides can result in formation of Fe and Al molybdates under laboratory conditions. This author pointed out the similarity between Mo and P fixation in acid soils. Molybdenum increases in solubility and availability with increasing pH. However, in contrast with P, Mo does not form a precipitate with Ca in the alkaline pH range, thereby increasing in availability beyond pH 6.5 (177).

The strength of adsorption of Mo on Fe oxides decreases with increasing pH. Several authors have postulated that molybdate ions replace surface hydeoxyl groups on the hydrous oxide film (197).

Sims and Bingham (332, 333) demonstrated that B retention by kaolinite and montmorillonite was largely due to the presence of Fe and Al forms, either as coatings on silicate mineral particles or as interlayer-contained materials. These authors also showed that hydroxy Fe and hydroxy Al were capable of B retention. The retention of B by these materials was found to be pH dependent with maximum retention in the alkaline range. The hydroxy-Al forms exhibited a greater B-retention capacity than the hydroxy-Fe forms.

Reaction with organic matter.--Hodgson (177) suggested that three systems should be recognized in describing the association between organic matter and heavy metals. First, reaction with a high molecular weight compound, such as lignin, results in immobilization of the metal. Low molecular weight compounds, such as short-chain organic acids and bases, appear to increase the solubility and movement of the metal. And last, some compounds are soluble when unassociated but form insoluble salts with heavy metals; the phytin salts of Fe and Al are an example of the last type.

Organic soils are usually associated with deficiency of several micronutrient elements, particularly Cu (177). Furthermore, the organic matter of organic soils shows a high value for heavy metal retention. Mulder, Lie, and Woldendorp (255) described several experiments conducted to demonstrate that the organic matter of organic soils was capable of Cu fixation. In one of these experiments, dilute $CuSO_4$ solutions were percolated through a soil column until the soil was Cu saturated; excess Cu was washed out with distilled water, and subsequently with a 1% $Ca(NO_3)_2$ solution to displace exchangeable Cu. Nonexchangeable Cu was determined by difference from the total amount retained. A soil on which plants were extremely Cu deficient was found to retain 73 mg of Cu/g of organic matter, one-third of which was in nonexchangeable form. Another soil supporting healthy plants retained 43 mg of Cu/g of organic matter, only 12% of which was nonexchangeable. In all cases nonexchangeable Cu was released by treatment with 0.05N HCl. Broadbent (57) found different types of Cu retention by soil organic matter by saturating organic matter preparations with Cu. These preparations were subsequently extracted with water, and 0.01, 0.05, 0.10, and 1.00N HCl solutions. In a similar experiment, Ennis and Brogan (116) reported that Cu retained by peat against 1N HCl extraction was unavailable to oat plants in sand culture; the Cu fraction resisting extraction with 0.1N HCl was slightly available; the residual Cu after 0.01N HCl extraction was more available but to a lesser degree than $CuSO_4$.

According to Mitchell (248) the nature of the organic compounds responsible for retention of micronutrients has been studied extensively; it appears that humic and fulvic acid fractions are mostly responsible for this process. This author (248) also explained that fulvic acid has a greater complexing capacity, and the resulting metal complexes are generally water soluble. Ennis (115) reported that carboxyl and hydroxyl groups were responsible for retention of 90% of the Cu added to peat samples. The same author (115) postulated that the more tenaciously bound Cu in his experiments may have formed complexes with amino groups. In addition, there is also evidence that sulfide groups produce very stable Cu complexes (115, 248). Mitchell (248) explained that complex formation between Cu and humic acid had an optimum pH of 2.5 to 3.5; for fulvic acid a pH of 6 was indicated as optimum for the same reaction. Zinc, Fe, Al, Co, and B have also been reported to form complexes with organic matter (248, 255). Hodgson (177) stated that some investigators have postulated that B may react with carbohydrates in the soil organic matter.

Soil reaction can affect the formation of metallo-organic complexes by controlling the extent of dissociation of the various binding sites. Soil reaction can also affect microbial activity, thereby affecting the relative abundance or stability of the organic compounds involved in metal complex formation (177).

Effect of Ca on Nutrient Absorption

The effect of Ca on the absorption of Al and Mn by plants was discussed in a preceding section. However, the Ca ion also has a significant effect on the absorption of other plant nutrients, particularly P, Mg, K, and B.

Phosphorus absorption.--Many investigators have reported that Ca stimulates P absorption by plants (135, 213, 308). However, some of these studies are inconclusive as they dealt with Ca concentrations that were deficient or P concentrations that were toxic to plants. A study by Robson, Edwards, and Loneragan (308) constitutes an exception in this respect. They studied P absorption by two *Medicago* species and two *Trifolium subterraneum* cultivars in flowing culture solutions kept at pH 5.4. Calcium concentrations in solution were maintained at 2.5×10^{-4} and 2.5×10^{-3}M. Phosphorus concentrations were maintained at 2.5×10^{-7} and 5.0×10^{-6}M. These Ca and P concentrations are within ranges commonly found in soils (28, 43, 52, 211, 313). The Ca concentrations in solution were not likely to be deficient based on experiments conducted by Loneragan and Snowball (221). Results from one of the Medicago species and one of the Trifolium subterraneum cultivars are presented in Table 2.

These data show that with the exception of Medicago truncatula at the lowest P concentration, increasing the Ca concentration in solution had no significant effect on plant growth, thereby eliminating any confounding effect of Ca on P absorption due to the alleviation of Ca deficiency. Calcium significantly increased P absorption by Medicago truncatula at the two P levels. An interaction with plant species was apparent; Ca also increased P absorption by Trifolium subterraneum but to a lesser degree and was statistically significant only at the highest P level. The authors (308) hypothesized that the greater sensitivity of Medicago species to soil acidity may be related to a higher Ca requirement for optimum P absorption by this plant.

Two mechanisms have been advanced to explain the effect of Ca on P absorption. Leggett, Galloway, and Gauch (213) postulated that Ca may increase the turnover of the phosphate absorption carrier. Hyde (185) and Franklin (135) suggested that Ca decreases the electronegative potential at the root surface, thereby increasing the effective phosphate concentration at the absorption sites.

Potassium and Mg absorption.--Bear and Prince (33) proposed the cation-equivalent concept for plants. They postulated that the meq sum of K^+, Ca^{2+}, Mg^{2+}, and Na^+ per unit of dry weight tends to remain

Table 2. Effect of Ca and P concentrations in solution on growth and total P content of *Trifolium subterraneum* L. and *Medicago truncatula* Gaert.

P conc	Ca conc	Dry-matter weight	P content
X10^{-6}M	X10^{-6}M	mg/plant	10^{-6} g/plant
		Trifolium subterraneum	
0.2	250	17.9 a*	55 a
	2,500	18.0 a	59 a
0.5	250	19.2 b	178 b
	2,500	20.6 b	257 c
		Medicago truncatula	
0.2	250	13.8 a	38 a
	2,500	16.1 b	52 b
0.5	250	16.5 b	148 c
	2,500	18.0 b	220 d

* Any numbers in a vertical column within plant species are significantly different at the 5% level if they are not followed by a common letter.

Data from Robson et al. (308).

constant in plants regardless of variations in the number of meq of individual cations. Thus, the application of Ca to the soil, for example, would increase the concentration of Ca in the plant, thereby decreasing the concentrations of K, Mg, and Na. Other investigators (34, 385) have indicated that the availability of K, Ca, and Mg to plants depends on their relative concentrations in the soil. They have proposed the use of K/Mg, K/Ca, and (Ca+Mg)/K ratios as availability indexes for these nutrients. According to this concept, the availability of K and Mg would be determined by their concentrations in the soil relative to that of Ca. However, Brown and Rouse (66) showed that application of K had no effect on the Ca concentration in T. repens. Martin, Vlamis, and Stice (235) reported that $CaSO_4$ increased Ca concentration in vetch (Vicia sativa L.) but had no effect on the Mg concentration. Viets (367) found that K uptake by excised barley roots increased with increased Ca concentration in solution. According to Barber (27), the availability of K appears to depend more on its absolute concentration in the soil than on its relation to Ca and Mg. In solution cultures, the effect of low Ca concentrations on K absorption appears to be stimulatory (27, 190). However, Adams and Pearson (3) indicated that lime-induced K deficiency was a serious problem in soils of low K content in the southeastern region of the United States.

Moore, Overstreet, and Jacobson (250) reported a 95% decrease in Mg uptake by excised barley roots when Ca was added to the solution at an equivalent concentration. Other investigators (191, 350) have postulated an inhibitory effect of Ca on the transport of Mg from roots to shoots, or on the distribution of Mg among various parts of plant tops.

Boron absorption.--The effect of lime on B-fixation capacities of soils was discussed in a preceding section. The Ca ion is also known to exert a physiological effect on the uptake of B by plants (172). Jones and Scarseth (195), Reeve and Shive (296), and Brennan and Shive (55) reported that added Ca accentuated B deficiency and decreased B toxicity. Some authors (231, 232) have reported that Ca was more mobile or soluble in the presence of B.

Adams and Pearson (3) indicated that B deficiency was recognized in the fields in the southern United States during the late 1930's and was usually associated with liming. These authors (3) explained that B was frequently found deficient in soils with a coarse texture and low organic matter content. Most of the lime-induced B deficiency cases cited by Adams and Pearson (3) were probably caused by substitution of limiting factors. These soils were sandy, acid, and Ca deficient and frequently responded well to liming. Increased plant growth made greater demands for other nutrients including B.

Legume-Rhizobia Symbiosis

The legume-*rhizobium* symbiosis involves the association of a microorganism with a higher plant. The kinds and quantities of nutrients required for the establishment of an effective symbiosis may be different from those required by the microorganisms or the plant alone. Some of these elements have already been discussed in relation to the growth of the host plant. Emphasis will be made in this section on those elements which are important for the growth of *Rhizobium*, the nodulation process, or the N-fixation reaction.

Calcium and Mg deficiencies.--Norris (264) concluded that *Rhizobium* whether of clover or cowpea type, did not require Ca for growth. This author indicated that Mg was the alkaline metal required by Rhizobium; apparent growth responses to additions of Ca to soils or clay media were due to displacement of Mg from exchange sites by Ca, making Mg more available to the bacteria. Similar results were obtained by additions of other elements which are capable of displacing Mg into solution. Norris (264) indicated that added Ca actually appeared to be inhibitory to the bacteria. These results were used by him to modify the agar culture medium for Rhizobium, which traditionally contained large quantities of $CaCO_3$ or $CaCl_2$. Considerable improvement in the growth of slow types of Rhizobium was obtained by eliminating Ca compounds from the growing media.

The conclusion reached by Norris (264) concerning the Ca requirement of Rhizobium was partially incorrect. Vincent (369) indicated that the need for this element by Rhizobium has been demonstrated in sufficiently critical experiments. Its absolute specific requirement is extremely low and this may account for the results obtained by Norris. Strontium has been found to substitute Ca, with about one-fourth the efficiency, in maintaining normal growth and morphology. Neither Ba nor Mg has been found to be able to substitute for Ca (369). Vincent (369) explained that Mg is required by Rhizobium in greater concentrations and its deficiency can be demonstrated more easily than that of Ca. Under natural conditions, Ca is not likely to limit the growth of the bacteria unless its concentration is so low that the growth of the host plant would be severely affected (264, 369).

Vincent (369) called attention to Rhizobium's great need for divalent cations. For example, the total concentration of divalent cations required for optimum bacterial growth was found to be 20 times the Ca needed and 5 times the Mg. Vincent (369) explained that a deficiency of either element would cause a corresponding greater nonspecific demand for the other.

A reciprocal relationship appears to exist between H ion concentration and minimum Ca concentration required for adequate nodule formation. Munns (260) reported that when acidity increased from pH 5.6 to pH 4.8 the Ca concentration in solution culture required to nodulate 50% of Medicago sativa plants increased 60-fold. Initiation of infection was the most Ca-demanding stage at pH 5.2. Once infection was initiated, infection threads developed and nodules grew even when plants were transferred to solutions too low in Ca to have permitted infection to begin. Loneragan and Dowling (219) also showed that Ca had a specific role in nodule formation, and that the concentration required was far in excess to that needed for optimum growth of Rhizobium, or the unnodulated host plant. These authors (219) found that 10^{-4}M Ca solution was required for 50% nodulation of Trifolium subterraneum at pH 5.0. However, when acidity was increased to pH 4.2 the Ca concentration required was 100 times larger, or 10^{-2}M. The data reported by Loneragan and Dowling (219) also showed that growth of the clover host was little affected by a pH as low as 3.5 or a Ca concentration of 10^{-5}M. Thus, the inhibitory effects of these conditions on nodulation were not due to secondary effects on the plant.

The importance of this larger Ca requirement of legumes for adequate nodulation under field conditions was studied by Andrew and Norris (15). These authors found, working with a Ca deficient soil, that at the lowest level of lime at which nodulation of temperate species occurred, the nodules were few and tended to be large and multilobed. With each increment of $CaCO_3$ the number of nodules increased and tended to be smaller and single lobed. The nodulation of the temperate species was improved by $CaCO_3$ additions through 600 kg/ha. Trifolium repens was the only exception, being well nodulated without any added Ca. The tropical species, with the exception of Desmodium uncinatum, were well nodulated on unlimed soil. Liming had some effect on the growth of the tropical legumes but not on their degree of nodulation.

In 1955, Loneragan et al. (220) recommended in Australia the use of the lime-pelleting technique for clover seeds with the purpose of supplying Ca to the seedling. Hastings and Drake (162) in New Zealand modified this technique by using a 5% methyl-cellulose mixture instead of gum arabic as adhesive for the pellet. These investigators also used a mixture of dolomite and rock phosphate as a pellet coat instead of lime. Norris (269) indicated that many investigators have reported the need for peat culture in the pellet. According to Norris (269), the technique of lime pelleting is now a well-established commercial practice in Australia and New Zealand.

In 1965, Norris (267) reported that the cowpea Rhizobium produced alkaline metabolites whereas Rhizobium associated with temperate legumes excreted acids when grown in culture media. Later, the same author (268) warned against indiscriminate application of the lime-pelleting technique to tropical legume species. Norris (268, 269) pointed out that the cowpea Rhizobium may be intolerant of the alkalinity of the lime coat. Also, tropical legumes are naturally adapted to acid soils and require less Ca in the soil for optimum nodulation

(15). Norris (269) recommended a pellet coating made of inert materials such as rock phosphate dust. Souto and Dobereiner (339) reported from Brazil that seed pelleting with rock phosphate did not substitute for P and Ca fertilizer; this technique was found to increase Mn absorption and Ca deficiency symptoms when the seed was planted in soils with excessive Mn (339).

Hydrogen ion toxicity.--The detrimental effect of a high H ion concentration per se on the legume-Rhizobium symbiosis appears to be primarily on the survival of the bacteria rather than on the growth of the host plant or nodule formation and functioning (368, 369). Rhizobium species differ greatly in their tolerance to a high H ion concentration. Rhizobium meliloti is very acid sensitive; Rhizobium japonicum is very tolerant, having been reported to grow well at a pH of 3.5; Rhizobium trifolii is less sensitive to acid conditions than Rhizobium meliloti. Vincent (368) explained that Rhizobium trifolii is likely to be sparse in soils below pH 5, but with Rhizobium meliloti this would happen at a pH below 5.5. Mulder and van Veen (256) failed to obtain survival of Rhizobium trifolii in a soil of pH 5.1. These authors found that nodulation was successful only when the rate of inoculation was 60,000 cells/500 g of soil, with 20 clover plants sown on each pot; the authors pointed out that this practically made the soil a continuous rhizosphere.

Molybdenum deficiency.--Legumes have an absolute Mo requirement in common with all plants (172). Legumes, however, have also a specific requirement for Mo. This element is essential for N fixation by Rhizobium (369). Williams and Andrew (282) pointed out that most of the early responses to lime recorded in Australia were due to increased Mo availability. Molybdenum deficiency in Australia has generally been reported in acid soils, pH less than 5, with high content of Fe oxides; it has generally been found associated with P deficiency (171, 282).

The occurrence of Mo deficiency in Australia has also been reported to be affected by natural Mo reserves in the seed (171). Most of the Mo deficiency cases have been found with small seeded species such as Trifolium subterraneum, T. repens, alfalfa (Medicago sativa L.), and Melilotus indica (L.) All. (171). Mulder (254) indicated that alfalfa appeared to have a higher Mo requirement than some clovers, not only for the rhizobial system but probably also for the host plant.

In the absence of fixed N, Mo deficiency has been reported to greatly increase the number of root nodules; these nodules have been reported to be smaller than those of normal plants, with a brown or green coloration instead of the pink color of normal nodules (171, 172, 369).

Phosphate has been reported to have a direct effect on Mo uptake by legumes (171, 369). Pearson and Johnson (277) indicated that, even when the effect of added P on yields was considered, it was evident that P increased Mo uptake by Trifolium subterraneum, possibly through a direct effect on the absorption process. These authors reported that the effect of P varied with soils and was greater in the presence of applied Mo.

The effect of lime on the availability of Mo was discussed in a preceding section. It is interesting to note that the effect of H ion concentration on Mo absorption by plants in solution culture is opposite to the effect observed in soils (277). This indicates that the beneficial effect of lime on Mo uptake by plants is generally related to decreased fixation of the element in the soil with increased pH. In acid soils with high contents of Al or Mn, liming may increase Mo uptake by reducing the concentration of Mn and Al in the soil solution (171). These metals have been found to interfere with the uptake and utilization of Mo by plants (369).

Vanadium (V) was reported to substitute Mo in N fixation by some nonsymbiotic microorganisms (171). However, V has been found to have no effect on N fixation by alfalfa and *Trifolium subterraneum* (171, 369) in the absence of Mo. Davies and Stockdill (103), working with *T. repens*, reported that V could substitute Mo in its specific role in N fixation.

Other trace elements.--Some investigators (150, 288) have reported that legumes that are dependent on symbiotically fixed N require Co. Vincent (369) pointed out that Co may be required for the production of Co-containing vitamin B_{12}. He indicated that vitamin B_{12} may be needed in the metabolism of the bacteria themselves. This vitamin has been shown to have an influence on the growth of *Rhizobium* in agar culture (224). Furthermore, vitamin B_{12} has been isolated from nodules of *Medicago* spp. and cells of *Rhizobium meliloti* (208). Hewitt (172) indicated that there have been some reports of B deficiency interfering with nodule function. A deficiency of B may restrict the supply of carbohydrates to N-fixation sites through its effect on the vascular system of the host plant (369). Iron has been suggested as a participant in N fixation as part of the leghaemoglobin of root nodules (363). Van Schreven (363) indicated that some evidence suggests that Cu has a role in the production of leghaemoglobin. However, Hallsworth (150) pointed out that the role of Cu in symbiotic N fixation was still not clear.

Mycorrhiza

Mycorrhiza, or fungus-root as the term implies, is the name given to a structure formed by symbiotic association between some types of fungi and roots of higher plants (283, 378). There are three morphological types of mycorrhiza: ectomycorrhiza, in which the fungus lives within the root cells and tissues; and ectendomycorrhiza, in which the fungus forms a net around the root but also penetrates the root tissue. Within each type there is considerable morphological and histological variation (155, 283).

Nutrient absorption.--Most of the work on nutrient uptake by mycorrhiza has been conducted with ectomycorrhiza (148). The fungus component of mycorrhiza is thought to utilize sugars and other growth materials, such as amino acids and B vitamins, from plant roots; in return, it passes phosphate and other minerals to the roots (8, 148, 155, 313). Ectomycorrhiza have been found to be unable to utilize cellulose and lignin in temperate forest soils; however, endomycorrhiza in tropical soils have been reported to be able to digest these compounds (378).

It was first postulated that the great efficiency of mycorrhiza in nutrient absorption arose primarily from an increased absorbing surface due to enhanced root proliferation; also, from the presence of large absorbing surfaces on the fungal hyphae (148). More recently, Harley (155) has demonstrated that the isolated fungal sheath can absorb ions more rapidly than the host root. Harley and McCready

(156) found, studying P uptake from KH_2PO_4 by mycorrhiza, that the fungus was mostly responsible for P uptake by infected roots from a solution with a P concentration less than 10^{-3}M. This finding is significant because P concentrations less than 10^{-3}M are very commonly found in soils (43, 308, 313). Russell (313), for example, indicated that P concentrations in the soil solution are generally less than 10^{-6} to 10^{-7}M in P deficient soils, and less than 10^{-4} to 10^{-5}M in soils well supplied with P. Harley and McCready (156) also found that the fungus component of mycorrhiza retained most of the P absorbed; its translocation to the host occurred very slowly. The absorbed P was passed to the host in appreciable amounts only when the external supply of P was limited. Other investigators (155, 157) have reported uptake of metallic ions by mycorrhiza. Fagus spp. mycorrhiza showed high efficiency to absorb metallic cations, particularly K (155). In contrast to P, metallic cations appear to be rapidly translocated to the host (155, 157). These facts, which indicate high efficiency of nutrient uptake by mycorrhiza, are consistent with field observations. For example, the nutrition of trees is known to be intimately tied to mycorrhizal development (148). For approximately 20 years in Puerto Rico, attempts to establish 26 pine species and strains on the island were completely unsuccessful. Seedlings grew poorly, became chlorotic, showed symptoms of acute P deficiency, and died. In 1955, soil inoculum containing mycorrhiza from a pine stand in the southeastern United States was introduced and the results were dramatically favorable. Thereafter, all seedlings introduced were inoculated and pine trees grow successfully on the island now (56). Daft and Nicolson (101) reported that endomycorrhiza

produced marked increases in P uptake by corn and tomatoes on P deficient soils in Scotland compared with uninfected plants.

Some investigators (67, 246, 303) have made claims of N fixation by some types of mycorrhiza. However, the evidence on this subject is still inconclusive. Most of the N gains recorded have been detected by Kjeldahl analysis and may have been subjected to sampling errors. Furthermore, when the fungus has been isolated from the field and its N-fixing capacity studied, little care has been taken to work with pure cultures, uncontaminated with bacteria. The existence of mycorrhiza-bacteria associations was demonstrated by Mosse (253). He found that mycorrhiza did not develop on clover seedlings inoculated with spores of the fungus Endogone sp. unless a third organism, a species of Pseudomonas, was present in the mycosphere. A wide variety of species of Pseudomonas have been shown to fix N (10, 201).

Mycorrhiza in tropical acid soils.--According to Russell (313), soil conditions which favor the formation of mycorrhiza are: an adequate supply of humus; good soil aeration; and restricted supply of nutrients, particularly N and P. An intense photosynthetic rate by the host plant also favors mycorrhiza development (8). Therefore, the tropical environment offers an excellent habitat for the proliferation of mycorrhiza. Soils, particularly the older and more weathered types, are leached and poorly supplied with available N and P. Structure and drainage, and consequently aeration, are excellent in many of these soils (287, 313). Organic matter decomposition is rapid due to the high temperature and rainfall. Photosynthesis in tropical regions proceeds at an intense rate due to large amounts of solar radiation and high temperatures. All these conditions are conducive to the establishment of abundant mycorrhiza. Went and Stark (378) indicated that tropical rain forests have mainly endomycorrhiza which decompose woody fruits and other litter on the forest floor. These authors explained that mycorrhiza are very abundant in the surface layer of the soil where they absorb and store soluble minerals which otherwise would be leached away. Thus, the role of mycorrhiza in the soil-vegetation recycling process may be of considerable importance in tropical rain forests.

Mycorrhiza of Pinus spp. have been reported to be unable to grow profusely in some neutral or alkaline soils (302). This has generally been interpreted to mean that mycorrhizal fungi are acidophilic. However, Richards (302, 304) conducted experiments with Pinus caribae Morelet; his results indicated that the inability of mycorrhiza to develop in some alkaline soils was related to the mineral nutrition of the host plant rather than to a direct effect of the high OH ion concentration. Richards (304) found that mycorrhizal development was reduced by increasing the level of soil NO_3^-, either by adding NH_4NO_3 or by liming. This author (302, 304) also reported that liming reduced mycorrhizal development in the soils by inducing Fe deficiency in the host when the pH was about 7.5. Normal mycorrhizal development was restored without altering the pH by applications of Fe-EDTA either to the soil or to the foliage. In one experiment, Richards (302) found that NH_4NO_3 greatly reduced mycorrhizal development at pH 5.5; however, Na_2CO_3 did not affect mycorrhizal growth even when the pH was raised to 7.4.

Nitrogen Mineralization and Nitrification

Organic matter decomposition.--Correlations between soil pH and decomposition of soil organic matter generally indicate that the rate of decomposition of soil organic matter is increased by liming (29, 46, 98). Bornemisza, Laroche, and Fassbender (46) reported that liming an acid Costa Rican Oxisol with 12, 24, and 36 meq of $CaCO_3$/100 g of soil increased organic matter decomposition, at the end of 6 months, from 18.3% in the control to 21.7% at the highest lime level. Black (43) cited several examples indicating that the effect of liming on organic matter decomposition may be temporary and may involve only a fraction of the organic matter. Thompson, Black, and Zoellner (356) studied CO_2 evolution, and N and P mineralization of 50 soil samples ranging in pH between 5.2 and 8.1. They found no increase in the rate of CO_2 production per unit of organic C. Similar results were found for the rate of N and P mineralization.

Nitrification.--The oxidation of NH_4^+ to NO_3^- is carried out by two kinds of autotrophic bacteria, Nitrosomonas and Nitrobacter. The former oxidizes NH_4^+ to NO_2^-, and Nitrobacter oxidizes NO_2^- to NO_3^- (8, 43). Both autotrophs are very sensitive to acidic conditions (43). The rate of nitrification proceeds at a slow rate in acid soils and is accelerated by liming (9). The optimum pH for Nitrosomonas has been reported to be between 7 and 9 for most strains investigated (9). Nitrobacter activity has been detected from pH 5 to 10, with optimum pH in the neutral to slightly alkaline range (7). Alexander (9) indicated that the growth of the nitrifier bacteria depends on the oxidation of NH_4^+; thus, the effect of soil pH on the oxidation reaction itself cannot be separated from the effect on the proliferation of the microorganisms.

Soil Acidity and Other Microorganisms

Rhizosphere acidity.--Plant roots excrete energy-rich organic compounds which promote microbial activity in the region immediately surrounding the roots, or rhizosphere (313). The acidity of the rhizosphere can be of greater significance than that of the root-free soil due to its greater concentration of microorganisms and its immediate proximity to the absorbing sites of the root. This is particularly important in relation to symbiotic and nonsymbiotic N fixers, mycorrhiza, phosphate-dissolving microorganisms, and root pathogens.

The acidity in the rhizosphere is very variable and generally higher than in the root-free soil (201). Considerable variation in rhizosphere acidity has been found among different plant species growing in the same soil, and even different roots of the same plant (61, 65). Jackson (190) explained that one cause of higher acidity in the rhizosphere may be selective absorption of cations and anions by roots, particularly N forms. Absorption of NO_3-N by roots generally decreases rhizosphere acidity while NH_4-N has the opposite effect. In acid soils, nitrifiers are relatively inactive (8) and the NH_4-N form predominates thereby inducing a lower pH in the rhizosphere. Plants vary in their ability to utilize NH_4-N and consequently in their effect on rhizosphere acidity.

The effect of N source on soil reaction is important. The detrimental effect of NO_3-N on mycorrhiza development has already been discussed. The germination of spores of Fusarium solani, and consequently the severity of the disease, has been found to increase when NH_4-N is used rather than NO_3-N (97, 360).

Another possible cause of the greater acidity of the rhizosphere is excretion of organic compounds by plant roots. Rovira (312) reviewed this subject extensively. He indicated that sugars, amino acids, organic acids, nucleotides, flavonones, biotin, panthothenate, and niacin are usually found in root exudates. The nature of the exudate may affect the acidity of the rhizosphere directly, as with organic acids; or indirectly, as with sugars and growth factors, which stimulate microbial activity and secretion of acid metabolites.

A third possible cause of rhizosphere acidity, and probably one of significance only at the microscopically visible root surface, is the presence of adsorbed H ions on root exchange sites (384).

Composition of the soil microflora.--In general, extreme acid or alkaline reactions inhibit the growth of many common bacteria. The optimum pH for bacterial growth, as cited in most soil science textbooks, is near neutrality (8, 43, 313); however, there are wide variations among individual species.

Many investigators have reported intolerance of Azotobacter to acid conditions (201). In an extensive review of the Azotobacteriaceae, Jensen (193) indicated that the lower pH limit for most strains of Azotobacter was near 6.0. Several acid-tolerant strains of Azotobacter have been reported, but they are not commonly found in soils (201). In soils, high content of organic matter (50) and high moisture conditions (245) appear to alleviate the detrimental effect of high acidity on the growth of Azotobacter. Beijerinckia, another nonsymbiotic N fixer, is well known for its tolerance to acid soil conditions (201). This aerobic, N-fixing microorganism grows well between pH 3 and 10, with optimum growth at pH 4 to 5 (201). Under natural conditions, *Beijerinckia* has been isolated from soils with pH as low as 3.8 (249); however, it is more abundant in moderately acid soils (249). *Beijerinckia* grows almost exclusively in tropical soils although it has also been isolated from temperate areas (11). These bacteria have generally been associated with Oxisols; however, their distribution has been reported to depend on acidity and temperature (346) and the presence of energy-rich soluble sugars (194).

Clostridium is an anaerobic, nonsymbiotic N-fixing bacterium found in most soils; its distribution does not appear to be determined by soil reaction (201). However, it has been demonstrated in pure culture that pH has an effect on the species composition (38). Jurgensen and Davey (201) indicated that the lack of a pH effect on *Clostridium* was probably due to formation of endospores, which serve as protection against adverse soil conditions. A number of other bacteria which are known to fix atmospheric N have been isolated from acid soils. *Bacillus polymexa* is an anaerobic N fixer which has been found in soils of pH as low as 4 (201). *Aerobacter aerogenes* is another anaerobic, N-fixing bacterium widely found in acid soils (344). Several species of the genus *Pseudomonas*, common in acid soils, have been reported to be able to fix N (10).

In general, actinomycetes are not tolerant of soil acidity, the population size being inversely related to soil pH (8). One of the early applications of this fact was in the control of potato scab which is produced by the actinomycete *Streptomyces scabies*. Potato scab is generally controlled in the field with application of S to the soil to lower the pH to 4.5 (43). Black (43) indicated that the H_2S produced during the microbiological oxidation of S has been found to be toxic to actinomycetes. Most strains of Streptomyces fail to proliferate below pH 5.0 (8). Alexander (8) indicated that liming generally favors proliferation of actinomycetes, their optimum pH value being between 6.5 and 8.0.

Fungi can grow over a wide range of pH values (8). Some species grow well in culture media at pH values as low as 2, and other species have been found active at a pH of 9 (8). However, the microbiological flora of acid soils is generally dominated by fungi. This is not so much because fungi grow better in acid soils, but because they have a wide adaptability to soil reaction and there are fewer bacteria and actinomycetes in acid soils (8, 43, 313).

Soil Structure Deterioration

Schuffelen and Middelburg (325) reported that liming an Oxisol from Java markedly decreased the water percolation rate through the soil. Permeability reached a minimum, 10% of that of the untreated soil, between pH 5 and 7; there was some increase in permeability from pH 7 to 7.6.

Venema (364) stated that red earths of the tropical regions, which resemble Oxisols and Ultisols of the 7th Approximation, have a typical crumb structure; this excellent structure is produced by kaolinite particles surrounded by films of Fe oxides; the Fe oxide serves to cement the particles together. This crumb structure has often been referred to as "pseudosand" in the literature (364). Several authors (325, 364) have reported deterioration of the structure of these soils as a result of liming.

The Chemical Nature of P Fixation

Soil P Forms

The earth crust contains an average of 0.12% P (189, 211). Mineral soils have a total P content between 0.02 and 0.5%, with an average of 0.05% (189). The organic P fraction usually represents 50% of the total P (189, 211); the remaining 50% consists of inorganic forms. The organic fraction is inert and participates in the reactions discussed here only after mineralization. The inorganic fraction constitutes the most active P fraction in the soil and exists in equilibrium with P in the soil solution. The concentration of P in the soil solution generally falls between 0.1 and 1.0 ppm (211) and represents the immediate source of P for plant uptake.

Fassbender et al. (122) determined the P forms in 110 Central American soils and classified the soils in two groups, namely: soils containing predominantly Ca phosphate, and soils in which Al and Fe phosphates dominated. These authors found that in the first group, total P values were lower (0.04 to 0.25%, average 0.09%), and inorganic P predominated (59% of the total). Soils in the second group showed higher total P content (0.03 to 0.25%, average 0.12%), and had almost equal contents of organic and inorganic P. Similar values for total P in tropical soils have been reported by other workers (102). Lower total P values have been reported by Viera and Bornemisza (366) in highly weathered soils from Brazil.

Inorganic P in soils has traditionally been grouped into several chemical forms, namely: Al phosphate, Fe phosphate, Ca phosphate and Al and Fe occluded phosphates (73, 189). Chang and Jackson (73) developed a fractionation procedure to determine the relative amounts of these forms in the soil. This fractionation procedure was improved by Fife (124, 125). In acid soils Al and Fe phosphates are the predominant forms (122, 189, 313). Iron phosphate is generally more abundant than Al phosphates unless the soil has been fertilized with soluble P relatively recently (122). In slightly acid, neutral, and alkaline soils, Ca phosphates are predominant (122, 189, 313). Fassbender et al. (122) found that in 110 Central American soils a pH of 5.5 represented the dividing line between predominance of Al and Fe phosphates and predominance of Ca phosphates. Occluded phosphates are only found in abundance in highly weathered soils such as the ferruginous Oxisols (189).

The P fractionation technique (73, 124, 125) is arbitrary to some extent. Phosphorus forms in soils are chemically heterogeneous, comprising many phosphatic compounds of each metal involved, with different compositions, degrees of crystallinity or amorphousness, and solubilities. Chemical extraction may cause chemical redistribution or readsorption of P forms in the soil; therefore, the form of P assumed to be extracted may not be that present in the chemically undisturbed soil.

Magnitude of P Fixation

Theoretically, P should be considered fixed in soils when it is converted into insoluble forms which have limited availability to plants. However, the term "fixation" has usually been used in the soil literature to mean P retention against chemical extraction; part of this P may be available to plants. Fixation, as used here, means retention against chemical extraction, not necessarily against plant uptake.

Soils can be deficient in plant available P, even if they contain large amounts of total P. For example, Fassbender et al. (122) reported for 110 Central American soils total P values in the order of 0.1%. However, most of the soils were extremely deficient in available P; only 15% of the soils showed an adequate supply based on greenhouse trials.

Since 1850, soils have been known to retain P against water extraction; however, major advances in the study of soil P retention have been accomplished in the last 40 years (167). Many investigators have studied retention of P, added in most cases as KH_2PO_4 or NaH_2PO_4, by soils against water extraction (118, 120, 309, 318). Fassbender (120) showed that P-retention capacities of 107 Central American soils ranged from 9.7 to 94.1%, with an average of 37.1%, when treated with 5,000 ppm of P from KH_2PO_4 for 6 hours; most soils showed a fixation capacity between 20 and 40%. Roeder and Bornemisza (309), using a technique similar to that used by Fassbender (120), reported higher P-fixation values, 84.2 to 91.8%, in seven highly weathered Oxisols in Maranhao, Brazil.

Fassbender (118), working with 14 acid soils from Costa Rica, observed that Andepts (Inceptisols) exhibited larger P-fixation capacities, average of 86.4%, than Oxisols, 58.2%, and alluvial soils (Inceptisols), 42.0%. Saunders (318) determined amounts of P retained by 50 New Zealand soils, developed under widely different parent materials and weathering regimes, when treated with 5,000 ppm of P from KH_2PO_4 for 24 hours. This author found that P-retention values, ranging from 9 to 93% of the added P, were closely related to parent material and degree of weathering. For example, for young soils, Saunders (318) found that P retention was generally very high (92%) for soils developed under andesitic volcanic ash, high (84%) for those under basalt scoria and flows, and medium (48%) for soils under rhyolitic volcanic ash. However, the degree of weathering interacted with parent material. Older, more weathered soils exhibited lower P-retention values when under basalt scoria and andesitic volcanic ash, but higher P retention when under rhyolitic volcanic ash.

Soil Materials and P Fixation

One experimental approach used by many workers in their search for the materials responsible for P fixation has been multiple regression analysis; that is, relating P-fixation values with soil properties and materials. Many of these investigators have found significant correlations between P fixation and certain soil properties, having assumed on that basis that such properties were responsible for P fixation. However, on interpreting those reports one must keep in mind that a significant correlation is not proof of a cause and effect relationship. The relationship between P fixation and soil materials may be direct, as with Al and Fe hydrous oxides, or indirect, as with soil pH.

In general, many investigators have found significant correlations between P fixation and organic matter (5, 62, 119, 120, 316, 318). Some workers (6, 83) have reported significant correlations between P fixation and Al extracted with 1N NH_4OAc at pH 4.8. However, Fassbender (120) and Ahenkorah (5) found no significant correlation between P fixation and extractable Al. Saunders (318) found close correlations between P fixation and Fe and Al in the soil, extracted with ammonium oxalate-oxalic acid at pH 3 and dithionite-citrate reagents. Fassbender (120) indicated that soil reaction and dithionite-citrate extractable Fe could account for most of the P-fixation capacities of 107 Central American soils. Similar findings, concerning Fe, have been reported by other investigators (5, 120, 316, 318). On the other hand, Saini and MacLean (316) and Bromfield (62) found that dithionite-citrate extractable Fe was not related to P fixation. Most investigators (62, 120, 316) have found no relationship between soil pH and P-fixation capacities of 107 Central American Inceptisols and Oxisols. A decrease in pH from 5 to 4 was correlated with an increase in P-fixation capacity from 45 to 88%. Phosphorus fixation was determined by treating the soil with 5,000 ppm of P from KH_2PO_4 for 6 hours.

The role of organic matter in P fixation has been the subject of interesting speculation in the soil literature. It is not clear whether organic matter plays a direct or an indirect role in P fixation. Organic matter and Al are usually interrelated (120, 316). Fassbender (120) found a greater correlation between P-fixation capacity and soil organic matter for Andepts than for Oxisols. Alcagaya (6) reported similar results in 260 soils in Chile derived from volcanic ash. Aluminum is known to have a stabilizing effect on organic matter in Andepts, soils derived from volcanic ash (189, 313). Therefore, organic matter may be indirectly correlated with P fixation in those soils. In Spodosols, organic matter accumulation depends on pH and microbiological conditions, rather than on the stabilizing effect of Al. Organic matter may also play a direct role in soil P fixation; the presence of electropositive charges in organic groups (381) may lead to the retention of $H_2PO_4^-$. Mattson et al., cited by Saunders (318), postulated the existence of a gel complex, an Al and Fe phospho-silico-hydroxy humate, formed by precipitation of ionic forms of Al and Fe by different anions, including phosphates, in the presence of organic matter.

Mechanisms of P Fixation

The reactions by which P becomes fixed in soils have generally been grouped in three classes: isomorphous substitution, precipitation, and adsorption. All of these reactions involve mainly two ionic forms of the orthophosphoric acid. Buehrer (69) calculated, from dissociation constants, that H_3PO_4 only exists in solution in appreciable concentrations below pH 2. The species $H_2PO_4^-$ and HPO_4^{2-} are the most abundant in the pH range encountered in soils.

Isomorphous substitution.--This process generally begins as an adsorption reaction (313). Some of the phosphate moves into lattice spaces of molecular dimensions and replaces OH and silicate anions from the crystal lattice (189). Stout (345) studying alumino-silicate minerals indicated that a reversible ionic exchange occurs between phosphate and OH ions. This author (345) postulated that phosphate ions can reach and replace the OH ions by entering between alumino-silicate layers. Toth (359) found that, as P fixation increased, the amount of silica in the supernatant liquid also increased. This author (359) postulated that silicate was displaced from the soil colloid by phosphate. Marshall (233) indicated that P could replace Si in the mineral lattice since it has a valency of 5+ and is smaller than Si; thus, it would cause no disturbance in the lattice framework.

The process of isomorphous substitution proceeds at a slow rate; its relative importance in P fixation insoils is not clear (203, 313). Probably, this process is of significance only after a prolonged time period.

Precipitation.--The presence of crystalline Al, Fe, and Ca phosphates in soils has been postulated from solubility product considerations (84). Crystalline Al and Fe phosphates such as variscite and strengite are extremely insoluble (313). However, fresh Al and Fe phosphates precipitated at room temperature are moderately available to plants (182, 313). It is reasonable to expect the formation of metal phosphates of several kinds under soil conditions. Soil chemists have postulated the precipitation concept as a mechanism of P fixation assuming that Al and Fe phosphates, which are usually amorphous, crystallize to more insoluble forms after prolonged aging. It is difficult to estimate quantitatively how much applied P is fixed in soils in the form of precipitated Al and Fe phosphates; Taylor, Gurney, and Lindsay (353) found that crystal type, degree of crystallinity, and soil pH were more important than the metals involved, Al or Fe, in determining the availability of the phosphate to plants.

Kittrick and Jackson (204, 205, 206, 207) showed that P can be precipitated by Al and Fe hydrous oxides, and that P fixation by this mechanism can be explained on the basis of the solubility product principle; the compounds formed were hydroxy-Al or hydroxy-Fe phosphate. This agrees with the fact that $FePO_4$ and $AlPO_4$ are not likely to occur in soils; in the pH range of soils the compounds more likely to be formed are Fe or $Al(H_2O)_3(OH)_2H_2PO_4$ (167).

Some investigators (204, 298) have shown, with electron micrographs, that kaolinite will dissolve in the presence of phosphate at 90C and Al phosphate will form, leaving no traces of the kaolinite after 31 days. This reaction was first postulated by Low and Black (223) who indicated that kaolinite dissociated into Al and silicate ions in accordance with the solubility product principle. In solutions containing phosphate, the dissociation of kaolinite increased because phosphate precipitated Al disturbing the equilibrium, and causing more kaolinite to dissolve. Hsu (182) explained that when phosphate reacts with kaolinite the reaction can be considered precipitation or adsorption. Precipitation occurs when phosphate removes Al completely from the lattice and reprecipitates as a new phase. Adsorption occurs when phosphate breaks only part of the Si-O-Al or Al-OH bond, reacting with Al still in the lattice.

Adsorption.--This mechanism has been postulated for certain reactions between phosphate and several soil materials, namely: clays, Al and Fe hydrous oxides, exchangeable Al, and hydroxy-Al and hydroxy-Fe polymers.

Several authors have reported phosphate adsorption by montmorillonite (95, 113, 319). Scarseth (319) proposed that phosphate was retained by bentonite by exchange of phosphate ions for OH ions at the edge of the crystal lattice. However, recent findings seem to indicate that Al and Fe sesquioxides on the clay may have been responsible for the P adsorption reported in the literature. For example, Coleman (95) indicated that phosphate retention by bentonite was greatly decreased by removal of Al and Fe oxides from the system. Fried and Dean (138) reported phosphate retention by surface coatings of Al and Fe oxides on clays and exchange resins; these authors indicated that in a mixed Fe-Al system most of the phosphate was retained by the ferrated resin.

In alkaline soils, some authors have reported phosphate retention by a H_2PO_4-Ca-clay linkage (138, 319). Ellis and Truog (113) found that phosphate retention by Ca-saturated bentonite was much greater than for Na- or Al-saturated clays. These authors (113) postulated precipitation of Ca phosphate on the surface of the clay. However, in acid soils Ca is not likely to be responsible for phosphate retention below pH 5.5 (167, 203).

In 1950, Low and Black (223) reported that, at low P concentrations and temperature, phosphate retention by kaolinite could be described by the Freundlich adsorption isotherm. They concluded that the reaction was a chemisorption between phosphate and OH ions at the edges of the clay mineral. The conclusions reached by these authors (223) were incorrect insofar as the Freundlich adsorption isotherm is not proof of adsorption. This type of isotherm is used to describe a known adsorption reaction (230), However, it can also describe other types of reactions, i.e., a precipitation reaction controlled by ionic exchange. An example of the last type of reaction was provided by Russell and Low (314). These authors also reported a typical adsorption curve, obeying the Freundlich equation, for phosphate retention by kaolinite. Since saturating the exchange complex with Al increased phosphate retention, they (314) postulated that exchangeable Al reacted with added phosphate to form Al phosphate on the kaolinite surface.

In strongly acid soils, exchangeable Al may be present in appreciable amounts and precipitate added phosphates. However, since acid soils also have large amounts of amorphous hydroxy-Al and hydroxy-Fe monomers and polymers, surface adsorption on these soil components may constitute the more important reaction in early stages of P fixation. Hsu and Bates (183) postulated the formation of positively charged hydroxy-Al polymers when Al is neutralized with a base. The Al ions on the surface of the polymer are not completely neutralized until the pH reaches a value of around 8; thus, they can react with the phosphate ion. Hsu (182) stated that the reaction between phosphate ions and hydroxy-Al polymers can be considered precipitation or adsorption depending on the size of the polymer, which in turn depends on the pH, and the phosphate concentration in solution. The same author (182) indicated that at pH 4, with high phosphate concentration, the reaction may result in the formation of $Al_6(OH)_{12}(H_2PO_4)_6$. In a slightly acidic to neutral, pH 6 to 7, dilute phosphate solution, hydroxy-Al polymers are stable and phosphate is adsorbed on the surface. At a higher phosphate concentration, the hydroxy-Al polymer can break down to the 6-member ring unit even at pH 7. It is also possible that in dilute phosphate solutions, phosphate may not precipitate but remains in solution as a partially neutralized and positively charged complex (182). Precipitation or adsorption may be indistinguishable when Al is present as polymers of intermediate size (183). Hsu (182) indicated that hydrolysis, polymerization, and reaction of Fe with phosphate follows a similar mechanism to that of Al. However, hydroxy-Fe polymers and Fe hydroxides appear to be unstable and change to oxides after prolonged aging (182).

Hsu (182) described how precipitation and adsorption reactions could control phosphate concentration in the soil solution. He stated that in a precipitation reaction Al phosphate is in equilibrium with Al and phosphate ions in solution; the concentration of phosphate in solution is controlled by the solubility of the precipitated compound, and not by the amount of phosphate precipitated. In an adsorption reaction, on the other hand, the concentration of phosphate in solution increases as phosphate adsorption proceeds; when the surface is almost saturated, the adsorbed phosphate may be easily available to plants; however, at low saturations, phosphate may be little available.

The above-mentioned considerations imply that precipitation and adsorption reactions would yield two major types of graphical representations of P added versus P extracted. Phosphorus extracted with water, for example, would increase linearly with increasing rates of P added to the soil if the reaction was primarily a precipitation. However, a hyperbolic increase in P extracted would be obtained if the phosphate was retained by adsorption.

The Region of Lake Izabal, Guatemala

Location

The Republic ofGuatemala is located southeast of Mexico. It is bordered on the north and west by Mexico; on the east by Belize, the Caribbean Sea, and Honduras; on the southeast by El Salvador; and on the south by the Pacific Ocean. Guatemala occupies a land area of 108,889 km^2 (42,042 sq. miles) with 4,209,820 people, and an annual rate of population growth of 3.1% (106). The Department of Izabal is located in the eastern section of Guatemala. Izabal has an area of

9,038 km^2, or 8.3% of the total area of Guatemala, and is the second largest Department in the country. According to the 1964 census (106), Izabal had 114,000 inhabitants.

Lake Izabal has an area of 590 km^2, with an elevation of 0.88 m above sea level. The Polochic River and numerous creeks drain into Lake Izabal. The Lake drains into the Caribbean Sea through the Dulce River. The mountains of Santa Cruz run along the northern side of the lake and those of Sierra de las Minas along the southern side (331). A map of the Lake Izabal Region is presented (Fig. 1), showing approximate locations of the two experimental sites, Finca Los Murcielagos and near the village of San Felipe.

Geology

According to Brooks[3], the main geological feature of the study area is a serpentine block that runs along the northern side of the lake. There are several limestone formations within the area which have contributed to the alluvial deposits in the proximity of the lake shore. Ancient lakebeds and river terrace formations are also found in some areas along the perimeter of the lake. Metamorphic rocks such as schist, gneiss, phyllite, and quartzite have been found on the southern side of the lake.

Vegetation

Snedaker[4] described successional vegetation around Lake Izabal.

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[3] Brooks, H. K., 1970. A preliminary report on Lake Izabal, geology-hydrology. Univ. Florida, Gainesville, Florida. Mimeo.

[4] Snedaker, S. C., 1970. Ecological studies on tropical moist forest succession in eastern lowland Guatemala. Ph.D. Diss., Univ. Florida, Gainesville, Florida.

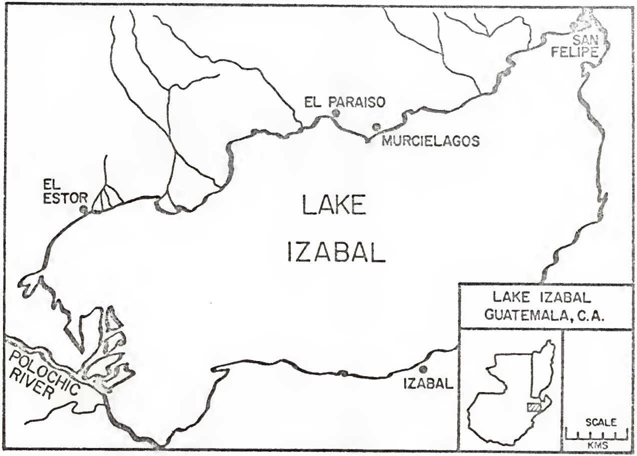

Fig. 1. Map of the Lake Izabal Region, Guatemala, Central America.

Source: Simmons, Tarano, and Pinto (331).

He indicated that the main vegetation type in the area is tropical rain forest. Among the broad-leaved trees are species that have been exploited for commercial purposes, such as *Swietenia* sp. (mahogany), *Cedrela* sp. (Spanish cedar), *Calophyllum* sp. (Santa Maria), and *Achras* sp. (Zapotilla). On upland areas, *Pinus caribea* grows on serpentine soils. In many places second-growth fallow vegetation replaced the mature forest after the areas were abandoned by farmers who practiced shifting cultivation.

Soils

The soils of Izabal have been described by Simmons et al. (331). These authors classified the soils on the lowlands of Finca Los Murcielagos as undifferentiated alluvial soils.

Soils at San Felipe, on the northeastern shore of Lake Izabal, were classified by Simmons et al. (331) as the Guapinol series. These authors cited the following main characteristics of this soil series:

Parent material: serpentine
Relief: from moderately to very steep (slope 20 to 40%)
Internal drainage: good
Surface soil
    color: reddish brown
    texture: clay
    thickness: 10 to 20 cm
Subsoil
    color: reddish brown
    consistency: friable
    texture: clay
    thickness: 40 to 50 cm
Water holding capacity: high
Hardpan: none
Erosion: considerable
Natural fertility: low
Management problem: soil fertility and erosion control

Climate

Snedaker[5] summarized climatological data collected for several years at Finca Los Murcielagos. The average annual precipitation from 1963 to 1967 at Finca Los Murcielagos was 1,887 mm (Table 3). The rainy season generally occurred between May and November. July was usually the month with the most precipitation; February was generally the driest month of the year, with an average monthly precipitation of 35.7 mm. During the rainy season there were usually two maximum rainfall peaks in July and September.

The mean maximum temperature at Finca Los Murcielagos from 1962 to 1967 was 30.7C (Table 4). The mean minimum temperature during that period was 21.3C. Maximum as well as minimum temperatures in the area were relatively constant throughout the year. The hottest hours in the day were those early in the afternoon, whereas the hours immediately before sunrise were usually the coolest.

The People and Their Agriculture

Most of the population in the Lake Izabal Region consists of Kekchi Indians who emigrated from the highlands of the Department of Alta Verapaz. They are usually hired as laborers on farms around the lake and are allowed to use small tracts of land for planting corn (Zea mays L.). Fishing is practiced, but it is not so common as corn growing. Shifting cultivation is the agricultural system generally used for growing corn. The term "shifting cultivation" is applied to any one of a number of agricultural systems in which tracts of

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[5] Snedaker, S. C., 1970. Ecological studies on tropical moist forest succession in eastern lowland Guatemala. Ph.D. Diss.,Univ. Florida, Gainesville, Florida.

Table 3. Monthly precipitation from 1963 to 1967 at Finca Los Murcielagos, Izabal, Guatemala.

Month	Years					
	1963	1964	1965	1966	1967	Mean
	Precipitation, mm					
Jan	85.9	45.0	132.3	NR	116.3	94.9
Feb	52.1	20.8	24.1	NR	35.1	33.0
March	158.5	47.2	14.7	100.6	90.4	82.3
April	38.4	94.5	32.3	45.7	80.5	58.3
May	131.1	208.8	127.0	179.1	183.0	165.8
June	227.8	234.4	197.6	315.5	271.8	249.4
July	285.5	244.9	327.2	293.6	290.1	288.3
Aug	132.3	176.0	215.4	243.8	232.4	200.0
Sept	394.0	95.5	271.5	312.7	292.6	273.3
Oct	183.6	78.2	NR*	204.2	295.4	190.4
Nov	121.2	230.4	NR	62.8	138.7	138.3
Dec	28.2	253.5	NR	39.1	66.8	96.9
Total	1,838.6	1,729.2			2,093.1	1,887.0

* Not recorded.

Source: Snedaker, S. C., 1970. Ecological studies on tropical moist forest succession in eastern lowland Guatemala. Ph.D. Diss., Univ. Florida, Gainesville, Florida.

Table 4. Monthly temperature characteristics from 1962 to 1967 for Finca Los Murcielagos, Izabal, Guatemala.

	Maximum temperatures		Minimum temperatures		
Month	Mean	Hour of occurrence	Mean	Hour of occurrence	Daily temp range
	C		C		C
Jan	28.0	14:2	19.1	4:50	8.9
Feb	29.6	14:19	19.6	5:14	10.0
March	31.3	14:30	20.4	4:51	10.9
April	32.9	14:43	21.2	4:44	11.7
May	33.3	14:25	22.4	4:35	10.9
June	31.9	14:33	22.9	4:49	9.0
July	31.3	14:20	23.4	4:37	7.9
Aug	31.9	14:43	23.1	4:49	8.8
Sept	32.0	14:37	23.0	4:57	9.0
Oct	30.5	13:59	21.7	5:03	8.8
Nov	29.1	13:37	20.4	4:55	8.7
Dec	27.8	13:25	18.8	4:44	9.0
Mean*	30.7	14:14	21.3	4:50	9.4

* Weighted means.

Source: Snedaker, S. C., 1970. Ecological studies on tropical moist forest succession in eastern lowland Guatemala. Ph.D. Diss., Univ. Florida, Gainesville, Florida.

forest are cleared by cutting and firing. The tracts are cropped for short periods of time and abandoned to secondary growth for intervals which always average longer than the periods of cropping.

Shifting cultivators prepare their corn fields during the dry season, January to April. Selection of planting sites is made subjectively considering drainage conditions and size of the vegetation. Many times a site that gave good yields 6 to 10 years before is selected again. The next step is to cut the vegetation using an ax for big trees and a machete for the more herbaceous undergrowth. The undergrowth is cut after the larger trees. After the vegetation is dry, and shortly before the onset of the rainy season, the site is burned. Fire is the most economical, and usually the only means that the farmer has for clearing the land. Four or 5 grains of corn are planted in holes about 10 cm deep made with a sharp-pointed stick. The corn field is weeded with a machete once or twice during the growing season. Weeds do not constitute a serious problem in first-year plantings on land previously under old vegetation. Second-year or older milpas (corn fields) usually contain more weeds. The next step is bending the corn stalks when the ears are fully developed, usually in September or October. The stalk is bent just below the ears so that the tip of the ear points downwards to prevent damage from birds and rain. The corn is left bent for 1 to 2 months until harvested in October, November or December. The harvested ears are usually stored in a field house on a wooden platform. The farmer husks the corn with a wooden pin and selects the best ears for seed.

MATERIALS AND METHODS

The general objectives of this investigation were to characterize the fertility status of three tropical soils, and to study the response of selected tropical legumes to applications of lime, P, and other nutrients.

Soil Fertility Characterization Experiment

The objective of this experiment was to characterize the nutritional status of three tropical soils in the greenhouse using the missing element technique.

The surface layer, 0 to 15 cm, of three tropical soils was used in this study: an Oxisol, Chacon series, collected near the village of San Felipe, Izabal, Guatemala; an Inceptisol, Suelos Aluviales series, collected at Finca Los Murcielagos, Izabal, Guatemala; and an Entisol, series unclassified, obtained from Dr. William Blue (Soil Science Department, Univ. Florida, Gainesville, Florida) collected at Los Diamantes Experiment Station, Guapiles, Costa Rica. Hereafter, these soils will be referred to simply as the Oxisol, Inceptisol, and Entisol, respectively.

Nutrients for each treatment were applied as shown in Table 5. Treatments consisted of the following nutrient combinations: control; complete fertilization; complete minus P; complete minus K; complete minus Ca; complete minus Mg; complete minus S; complete minus Cu and Zn; complete minus Mn; complete minus B; complete minus Mo; and

Table 5. Nutrient sources and rates used in the soil fertility characterization experiment.

Nutrient applied		Nutrient source	Nutrient conc in the source
Symbol	Rate		
	ppm		%
P	150	$Na_2H_2PO_4 \cdot H_2O$	22.4
K	150	K_2CO_3	56.6
Ca	200	$Ca(C_2H_3O_2) \cdot H_2O$	22.8
Mg	75	$MgCO_3$	29.0
S	50	Na_2SO_4	22.6
Cu	2	Na_2Cu chelate*	13.0
Zn	2	Na_2Zn chelate**	14.2
Mn	3	Mn-NTA-2 chelate#	8.2
Fe	5	138-Fe chelate&	6.0
B	2	$Na_2B_4O_7 \cdot 10H_2O$	11.3
Mo	1	$Na_2MoO_4 \cdot 2H_2O$	39.6

* Disodium cupric ethylenediamine tetraacetate trihydrate. Geigy Agricultural Chemicals, Ardsley, N.Y.

** Disodium zinc ethylenediamine tetraacetate dihydrate. Geigy Agricultural Chemicals, Ardsley, N.Y.

Manganese nitrilotriacetate. Monsanto Chemical Co., St. Louis, Mo.

& Sodium ferric ethylenediamine di-(o-hydroxyphenylacetate). Geigy Agricultural Chemicals, Ardsley, N.Y.

complete minus Fe. Each treatment consisted of three replications arranged in a completely randomized block design. The positions of the pot were randomized twice during the experimental period.

Solutions containing the appropriate fertilizer salts for each treatment were added to 2 kg of air-dry soil contained in individual plastic pots. The soil was wet to its water holding capacity and allowed to dry. After drying, the soil was removed, mixed thoroughly in a rotary mixer, and replaced into a pot which contained 0.2 kg of pea gravel.

A liberal amount of seed[1] of P. lathyroides (Phaseolus lathyroides L.) was inoculated with a commercial Rhizobium preparation[1] and sowed the same day, on February 24, 1970. The seed germinated within 3 days. After 2 weeks, the plant stand was thinned out to five seedlings per pot.

Distilled water was used to water the soil. The water holding capacity of each soil was determined by saturating the soil with water and allowing it to drain freely. The soil was brought to this moisture level by weighing each pot daily. After a few weeks, it appeared that watering at 100 ml/day was adequate for small plants; for larger plants, 200 to 250 ml/day were required to keep an adequate soil moisture status. Plants were sprayed with Sevin and Zineb every month to prevent insect and disease attacks.

Plant tops were cut, approximately 1 cm above the soil surface, 10 weeks after planting. Plants were then dried to constant weight at 70C, and dry-matter production per pot was determined by weighing. The Inceptisol was passed through a 4-mm screen and the roots collected. The roots were washed with water under pressure and dried to constant weight at 70C. Dry weights of the roots in each pot were recorded.

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[1] Obtained from Andersons Seeds Ltd., Summer Hill, Australia.

Liming Experiments

The objective of these experiments was to investigate legume response to liming as affected by soil group, legume species, and application of P and other nutrients.

Experiment 1

The objective of this experiment was to investigate the response of a tropical and a temperate legume to liming and P fertilization on a tropical Oxisol and a Florida Spodosol.

Centrosema (*Centrosema pubescens* Benth.) and *T. repens* (*Trifolium repens* L.) were used as representatives of tropical and temperate legumes, respectively. Phosphorus was applied as $NaH_2PO_4 \cdot H_2O$ at rates of 0, 25, 50, and 75 ppm of P. Liming rates were 0, 600, 1,200, and 1,800 ppm of $CaCO_3$. The experiment was a $3^2 \times 2^2$ factorial. The treatment arrangement was a completely randomized design with three replications. Pot positions were randomized every month.

Two kilograms of soil were mixed with the amount of $CaCO_3$ required for each treatment and placed into individual plastic pots. The soil in each pot was wet to its water holding capacity and incubated at approximately 20 to 35C for 2 weeks. Then, P was applied in solution to the soil at the required rate. Soils in all pots received a basal fertilization consisting of: 150 ppm of K, as KCl; 100 ppm of Mg, as

$MgSO_4 \cdot 7H_2O$; 50 ppm of S, as $MgSO_4 \cdot 7H_2O$, $ZnSO_4 \cdot 7H_2O$, and $CuSO_4 \cdot 5H_2O$; 5 ppm of Cu, as $CuSO_4 \cdot 5H_2O$; 10 ppm of Zn, as $ZnSO_4 \cdot 7H_2O$; 10 ppm of Mn, as $MnCl_2 \cdot 4H_2O$; 5 ppm of B, as $Na_2B_4O_7 \cdot 10H_2O$; and 0.5 ppm of Mo, as $NaMoO_4 \cdot 2H_2O$. The dry soil was then mixed thoroughly in a rotary mixer and replaced into each pot. The experiment was planted[2] on April 10, 1968. The first harvest was conducted after 18 weeks for Centrosema and 14 weeks for T. repens. Planting, plant population, watering and harvesting followed procedures similar to those used in the soil fertility characterization experiment. The experiment was replanted to Centrosema on September 20, 1969, and plant tops were harvested 18 weeks later.

Experiment 2

The objective of this experiment was to study the response of two tropical legumes to liming as affected by the application of all essential plant nutrients, with the exception of N, to an Oxisol and Entisol.

Phosphorus was applied as $Na_2H_2PO_4 \cdot H_2O$ at rates of 0 and 50 ppm of P. Lime rates were 0, 600, 1,200, and 1,800 ppm of $CaCO_3$. Other nutrients were applied in three combinations, namely: control; application of all nutrients but N; and application of all nutrients but N and Fe. Iron was omitted from the last nutrient combination to investigate the possibility of lime-induced Fe chlorosis. Nutrient sources and rates of application are shown in Table 6. Each treatment

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[2] Seeds and Rhizobium inoculant for T. repens were obtained from Andersons Seeds Ltd., Summer Hill, Australia. Rhizobium inoculant for Centrosema was obtained from Dr. D. O. Norris, Cunningham Laboratory, Brisbane, Australia.

Table 6. Nutrient sources and rates used in liming experiment 2.

Nutrient applied		Nutrient source	Nutrient conc in the source
Symbol	Rate		
	ppm		%
K	150	K_2CO_3	56.6
Mg	125	MgO	60.3
S	50	Na_2SO_4	22.6
Cu	5	Na_2Cu chelate*	13.0
Zn	10	Na_2Zn chelate**	14.2
Mn	20	Mn-NTA-2#	8.2
Fe	20	138-Fe chelate&	6.0
B	5	$Na_2B_4O_7 \cdot 10H_2O$	11.3
MO	5	$Na_2MoO_4 \cdot 2H_2O$	39.6

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* Disodium cupric ethylenediamine tetraacetate trihydrate. Geigy Agricultural Chemicals, Ardsley, N.Y.

** Disodium zinc ethylenediamine tetraacetate dihydrate. Geigy Agricultural Chemicals, Ardsley, N.Y.

# Manganese nitrilotriacetate. Monsanto Chemical Co., St. Louis, Mo.

& Sodium ferric ethylenediamine di-(o-hydroxyphenylacetate). Geigy Agricultural Chemicals, Ardsley, N.Y.

consisted of four replications arranged in a completely randomized block design. Pot positions were randomized every month.

Two kilograms of soil were mixed with the amount of $CaCO_3$ required for each treatment and incubated in moist condition at approximately 20 to 35C for 2 weeks. Phosphorus and other nutrients were applied in solution to the soil. After drying, the soil from each pot was mixed thoroughly in a rotary mixer and replaced into a pot which contained 0.2 kg of pea gravel. *Phaseolus lathyroides*[3] was planted on April 12, 1970. Plant tops and roots were harvested 10 weeks later. After plant roots were removed, the soil in each pot was mixed thoroughly in a rotary mixer. The experiment was replanted to Siratro (*Phaseolus atropurpureus* DC.) on February 5, 1971, and plant tops were harvested 14 weeks later. Planting, watering, harvesting, and other greenhouse operations were performed as described for the soil fertility characterization experiment.

Phosphorus Experiments

The objectives of these experiments were to determine the P-retention capacities of three tropical soils and a Florida Spodosol by laboratory techniques, and to study the response of two tropical legumes to P fertilization under greenhouse and field conditions.

Experiment 1

The objective of this experiment was to determine the P-retention capacities of an Oxisol, Inceptisol, Entisol, and a Florida Spodosol by laboratory techniques.

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[3] Source of seed and *Rhizobium* inoculant: Andersons Seeds Ltd., Summer Hill, Australia.

Five-gram samples of air-dry soil were treated with 2-ml solutions of $Ca(H_2PO_4)_2$ to give final concentrations of P in the soil of 0, 150, 200, 300, and 500 ppm, as described by Waugh and Fitts (377). The soil was incubated for 72 hours at room temperature, approximately 25C, and then extracted with 20 ml of Bray-P2 reagent, 0.03N NH_4F and 0.1N HCl (53). Plots of P extracted versus P applied were made for each soil.

Experiment 2

The objective of this experiment was to study the response of two tropical legumes to P applied to the Oxisol, Inceptisol, and Entisol under greenhouse conditions.

Originally, the amount of P to be applied in this greenhouse experiment was to be calculated from information obtained in liming experiment 1. The idea was to select the rate of applied P that would produce a sudden increase in extractable P. Theoretically, this rate would more than overcome the effect of P fixation and supply the soil with plant-available P. This rate would be designated as X value. However, since there was no sudden increase in extractable P at any rate within the P range studied, 100 ppm was selected as an approximation for the X value for all soils; this approach followed suggestions made by Waugh and Fitts (377). Phosphorus was applied to the Oxisol, Inceptisol, and Entisol at rates of 0, 50, 100, and 200 ppm. The required rate of P, as $Ca(H_2PO_4)_2$, for each treatment was dissolved in 250 ml of distilled water and added to 2 kg of soil contained in plastic pots. The soil was watered to its water holding capacity and incubated at approximately 20 to 35C for 1 week. All pots received a basal fertilization similar to that used in liming experiment 1.

After drying, the soil was mixed thoroughly in a rotary mixer and replaced into a pot which contained 0.2 kg of pea gravel. Phaseolus lathyroides was planted on February 23, 1970, and plant tops and roots were harvested 3 months later. The Inceptisol and Oxisol were replanted to Siratro on June 27, 1970, and plant tops and roots were harvested 14 weeks later. Roots were rinsed with tap water. Plant tops and roots were dried to constant weight at 70C, and dry-matter yields were recorded. Planting, watering, and other greenhouse operations followed procedures similar to those used in the soil fertility characterization experiment.

Experiment 3

The objective of this experiment was to study the response of three tropical legumes to P fertilization on two tropical soils under field conditions.

Location.--The experiment was located in the region of Lake Izabal in Guatemala, Central America. One experimental area was located at Finca Los Murcielagos, midway on the northern shore of the lake at 15° 35' north latitude and 89° 09' west longitude. The site had a level topography and was under pasture. The other site was located near the village of San Felipe, on the extreme eastern side of the north shore of the lake. The coordinates at this location were 15° 39' north latitude and 89° 00' west longitude. The area had a slope of approximately 5% and was covered by 5-year-old vegetation.

Treatments.--The soil at Finca Los Murcielagos was an Inceptisol of the Suelos Aluviales series. The soil at the site near the village of San Felipe was an Oxisol of the Chacon series (331). Profile descriptions of these two soils are presented in Table 7.

Three tropical legumes were used: Centrosema, Siratro, and S. humilis (Stylosanthes humilis HBK.). These species were considered among the most promising for the area.

Phosphorus was applied as triple superphosphate, 20.0% P, at rates of 0, 100, and 200 kg/ha of P. A second P application made at Finca Los Murcielagos after the first harvest raised the total rates to 0, 150, and 300 kg/ha of P, respectively. Molybdenum was applied, as $Na_2MoO_4 \cdot 2H_2O$, to all subplots at a rate of 1 kg/ha. The experiment was a 3^2 factorial with four replications. The design was a randomized complete block.

Plots at each location consisted of 36 subplots. Subplots were 3 X 2 m in size with alleys 0.75 m wide between subplots. The four blocks were arranged in such a manner as to keep variability among subplots in a block as small as possible. At Finca Los Murcielagos, the blocks were arranged as four quadrants in a square. At the site near the village of San Felipe, the blocks were laid out along a strip of land oriented east-west. Each block consisted of nine subplots, one for each treatment in the experiment.

Establishment and management.--At Finca Los Murcielagos, the land was broken with a disk-type plowing harrow to a depth of approximately 20 cm. It was then harrowed and leveled. At the site near San Felipe, the natural vegetation was cut by hand with a machete and removed from the plot with a rake. The soil was loosen to a depth of about 8 cm with a hoe.

Plots, blocks, and subplots were laid out and marked with 50-cm wooden sticks painted orange and red for easier identification. The experiment at Finca Los Murcielagos was fenced with three lines of barbed wire to prevent cattle from entering. Fencing was not considered necessary at the site near San Felipe.

Seeds were inoculated with the appropriate certified Rhizobium strain.[4] The inoculant was made into a slurry with water and applied to the seed. The seed was allowed to dry under the shade and planted the same day, on November 30 at San Felipe, and on December 5, 1968, at Finca Los Murcielagos. Planting was made in rows 1 m apart at the following seed rates: 20 kg/ha for Centrosema and Siratro, and 30 kg/ha for S. humilis. Three months later, Centrosema and particularly Siratro had completely covered the soil surface. Growth of S. humilis was poor due to the low seed quality.

Subplots were weeded by hand monthly during the first 2 months of the experiment, and every 2 weeks thereafter. Alleys between subplots were kept free of vegetation. Pests were prevented by spraying with Sevin and Zineb at a rate of 2 kg/ha. Seeds of Centrosema and Siratro were harvested on March 15 to 18, 1969, 14 weeks after planting. Siratro required a second seed collection 2 weeks later due to irregular maturity of the seed. Seed was not harvested from S. humilis due to its extremely poor growth.

Green matter was cut at both locations on March 27 to 29, 1969, 4 months after planting. The tops of two plants collected from the center of each subplot were kept in plastic bags and used later for moisture and chemical determinations. The remainder of the green matter was cut with a machete approximately 5 cm above the soil surface. The material collected was placed in large burlap bags and weighed before proceeding to the next subplot. A second green matter harvest of Centrosema and Siratro was made at Finca Los Murcielagos on June 28, 1969, 3 months after the first cut.

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[4] Seeds of Centrosema and Siratro, and the Rhizobium inoculant, were obtained from Andersons Seeds Ltd., Summer Hill, Australia. Seeds of S. humilis were obtained from Dr. A. Kretschmer, Jr., Indian River Field Laboratory, Florida Agricultural Experiment Stations, Fort Pierce, Florida.

Soil collection.--Composite soil samples, 20 cores, were obtained with a 2.5-cm diameter auger from each subplot immediately after the first harvest. Sampling depth was 0 to 5 and 5 to 15 cm at Finca Los Murcielagos, and 0 to 5 cm at the site near the village of San Felipe.

Soil was collected for greenhouse investigations from both locations at Finca Los Murcielagos and near San Felipe. Approximately 400 kg of surface soil, 0 to 15 cm, were collected in the proximity of the field experiments. The soil was air dried for several days. It was then passed through a 4-mm screen, bagged in double plastic and burlap bags and shipped to the University of Florida, Gainesville, Florida. The soil was fumigated with methyl bromide by the USDA Plant Quarantine Station upon arrival in Miami, Florida.

Laboratory Procedures

Soil Chemical Measurements

Soil pH was measured potentiometrically with a Corning pH meter model 7. The determinations were made in a 1:2.5 soil-solution ratio with distilled water, 1N KCl, and 0.01M $CaCl_2$. Soil suspensions were left standing for 12 hours and were stirred prior to the pH determination. Organic C was determined by the Walkley-Black wet-combustion method as modified by Walkley (373).

Cation exchange capacity (CEC) was determined by extraction with neutral 1N NH_4OAc, and Kjeldahl distillation of the adsorbed NH_4^+ using Na^+ as displacing ion as described by Chapman (74). Exchangeable K^+ and Na^+ were determined in the NH_4OAc extract using a Beckman B flame spectrophotometer. Exchangeable Ca^{2+} and Mg^{2+} were determined using a Perkin-Elmer Model 303 atomic absorption spectrophotometer.

Soil P was extracted by the methods of Bray and Kurtz (53), 0.03N NH_4F and 0.1N HCl; and by that of Mehlich as described by Nelson, Mehlich, and Winters (263), 0.05N HCl and 0.025 N H_2SO_4. Phosphorus was determined in the soil extract by the aminonaptholsulfonic acid-reduced molybdophosphoric blue color method of Fiske and Subbarow (126).

Lime requirement was determined by incubating, at approximately 25C, 10-g samples of soil with increments of $Ba(OH)_2$ in a 0.01M $CaCl_2$ solution for 24 hours. Increments of $Ba(OH)_2$ were equivalent to 0, 110, 225, 450, 895, and 1,790 ppm of $CaCO_3$ (280). Soil salinity was determined in a saturation extract as described by Richards (305, p. 7).

Soil Physical Measurements

Soil samples were prepared for X-ray diffraction analysis by the method described by Whittig (380). X-ray diffraction patterns of Mg- and K-saturated samples were obtained using Cu radiation with a Ni filter at a current of 10 ma.

Particle-size distribution was determined by the Bouyoucos hydrometer method (47). Samples were stirred in a mechanical blender for 20 min to insure complete dispersion of the soil.

Plant Chemical Analyses

Plant samples were dried at 70C to constant weight and were ground to pass a 20-mesh screen in a Wiley mill with stainless steel blades. Approximately 1-g plant samples were dry ashed in a muffle furnace at 450C for 4 hours. To dehydrate the Si, 20 ml of 40% HCl were added to the ash residue, allowed to evaporate to dryness on a hot plate, and heated for 30 min at approximately 100C; 10 to 15 ml of H_2O and 2.25 ml of 40% HCl were added to the ash, brought to a boil on a hot plate at approximately 150C, and filtered through a Whatman No. 32 filter paper (77). The filtrate was diluted to 50 ml and used for cation and P analyses.

Calcium, Mg, Mn,Cu, Zn, Fe, and Al were determined in the ash filtrate with a Perkin-Elmer Model 303 atomic absorption spectrophotometer. Procedures for these analyses were described by Breland (54). Potassium was determined with a Beckman B flame photometer. Phosphorus was analyzed by the amino-naptholsulfonic acid-reduced molybdophosphoric blue color method of Fiske and Subbarow (126). Total N in plants was determined by the micro-Kjeldahl method modified by adding salicylic acid as described by Volk-Fontein.[5]

Culture of Rhizobium in the Laboratory

Seeds of Centrosema used in liming experiment I were inoculated with a specific Rhizobium strain furnished by Dr. D. O. Norris (Cunningham Laboratory, Brisbane, Australia). The Rhizobium culture was received from Australia on agar medium in a small sealed bottle. Upon arrival, a loopful of bacteria growth was transferred to a bottle containing 99 ml of sterile distilled water. After thoroughly suspending the bacteria by shaking, 1 ml of the bacterial suspension was seeded into each of 10 petri dishes containing a modified yeast-mannitol medium as described by Norris (266). The petri dishes were incubated for several days at room temperature, approximately 25C. Then, the bacterial growth was washed off from the agar surface and the resulting suspension was applied to the seed and soil. Seeds were planted the day they were inoculated. All the bacteriological work was performed under aseptic conditions.

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[5] Unpublished mimeographed sheet. Department of Soil Science, Univ. Florida, Gainesville, Florida.

Soil Profile Description

Soil profile descriptions to a depth of 180 cm were made following instructions in the Soil Survey Manual, USDA Department of Agriculture (336). Briefly, records were made of: number, arrangement, depth, and thickness of soil horizons; structure; soil color, according to the field-wet Munsell color notation; soil reaction, determined colorimetrically with a simple field kit; depth of the water table; and drainage status of the profile. Note was taken of the topography and vegetation.

Statistical Analysis

The data obtained from field and greenhouse experiments were recorded on computer cards. The computer was programmed to run analyses of variance by single degrees of freedom. Treatment means were compared using Duncan's multiple-range test (109).

RESULTS AND DISCUSSION

Soil Characterization

Soil Profile Description

Four soils were used in this investigation. Profiles of the two soils used in field experimentation at Izabal, Guatemala, are described in detail (Table 7). Particle-size analysis is presented in Table 8.

An Inceptisol was described and sampled at Finca Los Murcielagos, Izabal, Guatemala, on level topography. The surface layer was very dark gray, medium textured, slightly acid, and slightly sticky and plastic. This layer had a blocky structure, was well drained, and contained abundant grass roots. It was underlaid by a dark reddish-brown B_2 horizon with slightly coarser texture and near neutral reaction (pH 6.7); this layer was well drained and slightly sticky and plastic. The horizon immediately below was very dark grayish brown, coarse textured, near neutral, well drained, and with granular structure. A dark-gray layer of very coarse sand from a riverbed was found at a depth of 125 cm. The water table was at a depth of 140 cm when sampled in January, 1969. A profile description of this soil is presented in Table 7. The soil at the sampling site was being used for pasture. Similar soils in adjacent areas were planted to corn and African oil palm. Some areas were covered with second-growth vegetation of different ages.

Table 7. Soil profile descriptions at Finca Los Murcielagos and near the village of San Felipe, Izabal, Guatemala.

Soil horizon	Depth cm	Description
		INCEPTISOL Finca Los Murcielagos
A1	0-15	Very dark gray (5 YR 3/1); slightly acid (pH 6.4); clay loam; blocky structure; slightly sticky and plastic; well drained; abundant fine and medium roots.
B2	15-45	Dark reddish brown (5 YR 3/3); neutral (pH 6.7); sandy clay loam; strong coarse blocky structure; slightly sticky and plastic; well drained; some medium-sized roots.
B3	45-125	Very dark grayish brown (10 YR 3/2); neutral (pH 6.7); sandy loam; granular structure; well drained.
C	125-180	Dark gray (N 3/0); very coarse sand from a riverbed; under water table.
		OXISOL San Felipe
A1	0-20	Dusky red (10 R 3/2); acid (pH 5.4); clay loam; blocky structure; sticky and plastic; well drained; many fine roots.
B21	20-50	Dark red (10 R 3/6); acid (pH 4.9); clay; blocky structure; sticky and plastic; well drained; large number of dark minerals and charcoal pieces; stoniness may hinder root penetration.
B22	50-125	Yellowish red (5 YR 4/8); acid (pH 5.5); clay; weak blocky structure; sticky and plastic; some dark minerals; well drained.
B23	125-180	Yellowish red (5 YR 5/8); acid (pH 5.4); sandy clay; weak blocky to granular; sticky and plastic; moist.

Table 8. Particle-size distribution of experimental soils.

Soil horizon	Soil depth	Particle-size distribution sand	silt	clay	Textural class
	cm	%			
			Oxisol		
A1	0-20	30.4	31.6	38.0	Clay loam
B21	20-50	26.4	27.6	46.0	Clay
B22	50-125	20.4	21.6	58.0	Clay
B23	125-180	20.4	17.6	62.0	Clay
			Inceptisol		
A1	0-15	33.2	28.8	38.8	Clay loam
B2	15-45	47.2	22.8	30.0	Sandy clay loam
B3	45-125	76.6	10.4	13.0	Sandy loam
			Entisol		
A1	0-15	64.2	15.9	19.9	Sandy loam
			Spodosol		
A1	0-15	90.8	5.0	4.2	Sand

An Oxisol was described and sampled near the village of San Felipe, Izabal, Guatemala, on gently sloping topography. The surface horizon was dusky red, medium textured, and acid (pH 5.4). This layer was sticky and plastic and had a blocky structure. Drainage conditions were good and many fine roots were present. The color of the B_2 horizon varied from dark red to yellowish red. This layer was fine textured, acid (pH 4.9 to 5.4), and very sticky and plastic. Dark concretions and charcoal fragments were easily discernible. This horizon was well drained; stoniness could affect root penetration. A profile description is given in Table 7. The soil at the sampling site was under 5-year-old secondary vegetation. Other adjacent areas with similar soils were supporting pasture and minor crops such as corn, plaintains, and pineapples.

Particle-Size Distribution

Soil texture determined in the field was briefly described in the preceding section. Laboratory data (Table 8) showed that the surface horizon of the Inceptisol at Finca Los Murcielagos contained approximately equal amounts of sand, silt, and clay; the silt content was 29%. Sand increased with depth reaching a maximum of 77% at 45 cm; clay, on the contrary, decreased to 13% at the same depth.

The Oxisol at San Felipe had also approximately equal percentages of sand, silt, and clay in the surface layer. Sand decreased with soil depth to 20% at 125 cm; clay increased to 62% at the same depth.

An Entisol from Los Diamantes, Costa Rica, had approximately equal percentages of clay and silt in the 0-15 cm layer; sand was 64%.

A Spodosol collected from the Beef Research Unit, University of Florida, Gainesville, Florida, contained 91% sand in the surface layer.

Chemical Properties

The Oxisol, Entisol, and Spodosol showed acid reactions (Table 9); pH values in water for the surface layer, or A_1 horizon, of these soils were 5.4, 5.8, and 4.6, respectively. The reaction of the Oxisol remained constant with soil depth with the exception of the B_{21} horizon which was 0.5 pH unit lower than the remainder of the profile. The reaction of the Inceptisol ranged from slightly acid, pH 6.4, in the surface layer to near neutral, pH 6.7, in the underlying soil.

Soil pH values measured in 1N KCl were 0.4 to 0.9 pH unit lower than those determined in water. Soil pH values in 1N KCl are affected by hydrolysis of Al replaced from colloidal surfaces by the K ion (281). Exchangeable H^+ can also be brought into solution by the neutral salt resulting in lower pH. Schofield and Taylor (324) proposed to measure soil pH in a 0.01M $CaCl_2$ solution. These authors indicated that a 0.01M $CaCl_2$ solution was equivalent to the electrolyte concentration in the soil solution of non-saline soils at optimum field moisture content. In general, pH values measured in 0.01M $CaCl_2$ were 0.2 to 0.5 units lower than those measured in water (Table 9). Subtracting 1.14, the value of 0.5p Ca in 0.01M $CaCl_2$, from the pH measured in $CaCl_2$, a value called lime potential is derived. Schofield and Taylor (324) suggested that soil reaction be expressed as lime potential values as they remain constant for any given soil for a wide range of electrolyte concentrations. The

Table 9. Chemical characteristics of the experimental soils.

		pH, 1:2.5			Lime potential		
Soil horizon	Soil depth	H_2O	1N KCl	0.01M $CaCl_2$	pH-0.5pCa	Organic C	Organic matter
	cm					%	%
							Oxisol
A1	0-20	5.4	4.8	5.1	3.96	2.01	3.47
B21	20-50	4.9	4.5	4.7	3.56	0.52	0.90
B22	50-125	5.5	4.8	4.9	3.76	0.20	0.34
B23	125-180	5.4	4.8	5.1	3.96	0.06	0.10
							Inceptisol
A1	0-15	6.4	5.8	6.2	5.05	4.32	7.45
B2	15-45	6.7	5.8	6.3	5.16	0.58	1.00
B3	45-125	6.7	6.1	6.7	5.56	0.20	0.34
							Entisol
A1	0-15	5.8	5.2	5.5	4.36	3.66	6.31
							Spodosol
A1	0-15	4.6	3.8	4.1	2.96	1.66	2.86

* Extracted with neutral 1N NH_4OAc.

Table 9. Continued

Extractable P		Extractable cations*						
Mehlich	Bray 2	Ca	Mg	K	Na	Al	CEC	Base saturation
------ppm------		-----------meq/100 g---------------------						%
7.0	3.5	3.10	3.04	0.12	0.17	0.06	8.7	73.9
2.2	0.0	1.95	1.29	0.08	0.17	0.06	7.2	49.0
0.6	0.1	1.85	1.50	0.07	0.17	0.10	7.6	48.0
0.0	0.0	6.38	10.0	0.13	0.23	0.00	16.1	100.0
10.4	3.5	6.83	39.58	0.37	0.21	0.00	30.8	100.0
2.4	0.1	1.70	26.67	0.19	0.13	0.00	20.1	100.0
0.1	0.0	0.65	14.70	0.12	0.13	0.00	11.6	100.0
7.3	44.5	6.05	1.92	1.28	0.10	0.02	35.0	26.7
9.2	4.1	0.70	0.06	0.51	0.08	0.04	4.5	30.0

purpose of measuring soil pH in a neutral salt solution is to take into account the effect that salts have on H ion activity in the soil solution.

Organic C, and consequently organic matter, values decreased with soil depth (Table 9). The Oxisol and Spodosol had relatively low organic C percentages; the Inceptisol and Entisol showed medium values, 7.4 and 6.3%, respectively.

Extractable-P values are of special interest in this investigation since field and greenhouse experiments dealt with various aspects of P fertilization. Soil P was extracted by the methods of Mehlich as described by Nelson et al. (263), 0.05N HCl and 0.025N H_2SO_4; and by that of Bray and Kurtz (53), 0.03N NH_4F and 0.1N HCl. Mehlich's extractant removed more P than Bray and Kurtz's extractant from all soils with the exception of the Entisol; in the latter soil, Bray's solution extracted approximately six times more P than Mehlich's (Table 9). All P values were extremely low except that extracted by Bray's reagent from the Entisol, which was 44.5 ppm. The highest extractable-P value obtained with Mehlich's extractant was 10.4 ppm for the Inceptisol; this is below the deficiency threshold value, 18 ppm, reported in the literature (263).

The Spodosol was very poorly supplied with all basic cations (Table 9). The Inceptisol contained as much as 40 meq of Mg/100 g, which reflected the fact that this soil was developed from serpentine. The Mg content of the Inceptisol decreased with soil depth. In contrast, the Oxisol had relatively low content of Mg in the three upper horizons; however, Mg values increased to 10 meq/100 g in the 125-180 cm layer. Extractable Ca in all soils was relatively low;

the Inceptisol and Entisol had 6.8 and 6.1 meq/100 g, respectively. The poor Ca status of the Oxisol and Inceptisol was further complicated by their large Mg contents.

Calcium to Mg ratios in the Inceptisol decreased with soil depth (Table 10); the smallest of the Ca/Mg ratios of surface soils were 0.17 for the Inceptisol and 1.02 for the Oxisol. Hardy and Rodriguez (154) recommended a Ca to Mg ratio of 4 for optimum plant growth in soils of Trinidad. Optimum absolute values for soil nutrient ratios are difficult to define because of soil and plant differences. However, values such as those shown in Table 10 for the Inceptisol and Oxisol seem extremely unfavorable to plant growth.

Extractable K was low in the Oxisol, 0.12 meq/100 g in the top 20 cm of soil (Table 9); however, the other soils were better supplied with this element; K contents in the surface soil were 0.37 meq/100 g for the Inceptisol, 1.28 meq/100 g for the Entisol, and 0.51 meq/100 g for the Spodosol. In general, Mg to K ratios were extremely large in the Oxisol and Inceptisol, and small in the Entisol and Spodosol (Table 10); Hardy and Rodriguez (154) recommended an optimum Mg to K ratio of 8.

Extractable Na ranged from 0.08 to 0.23 meq/100 g for all soils. Extractable Al was barely detectable in all soils (Table 9). It is doubtful that Al extracted with 1N NH_4OAc at pH 7 could be called exchangeable and thus be comparable to that extracted by a neutral salt. It is possible that exchangeable Al was initially extracted by the NH_4OAc; however, hydroxy-Al compounds may have formed at pH 7 and were retained by the soil during extraction.

Surface soils of the Inceptisol and Entisol showed high CEC

Table 10. Some extractable-nutrient ratios for an Oxisol, Inceptisol, Entisol, and Spodosol.

Soil horizon	Soil depth	Nutrient ratios		
		Ca/Mg	Mg/K	(Ca + Mg)/K
	cm			
		Oxisol		
A1	0-20	1.02	25.33	51.17
B21	20-50	1.51	16.12	40.50
B22	50-125	1.23	21.43	47.86
B23	125-180	0.64	76.92	126.00
		Inceptisol		
A1	0-15	0.17	106.97	125.43
B2	15-45	0.06	140.37	149.32
B3	45-125	0.04	118.08	127.92
		Entisol		
A1	0-15	3.15	1.50	6.23
		Spodosol		
A1	0-15	11.67	0.12	1.49

values, 31 and 35 meq/100 g, respectively (Table 9). The surface soil of the Oxisol had a CEC of 8.7 meq/100 g; this value seems relatively low. Martini (236) reported CEC values from 20 to 35 meq/100 g for 25 Costa Rican Oxisols, with approximately 6 to 8% organic matter. The Spodosol had a CEC of 4.5 meq/100 g, which reflected its low organic matter content and sandy texture.

Data in Table 9 show evidence that CEC measured with neutral 1N NH_4OAc may have been influenced by dissolution of Mg silicates in the extracting solution. For example, the CEC for the three top horizons of the Oxisol was approximately constant, from 7 to 9 meq/100 g; however, it increased to 16.1 meq/100 g in the B23 horizon. This increase can not be accounted for by differences in organic matter, clay content, or clay type. Organic matter decreased from 3.5% in the surface soil to 0.1 in the B23 horizon. There was an increase in clay content with soil depth (Table 8), but this was not sufficiently large to account for the observed increase in CEC, particularly between the B22 and B23 horizons. The B3 horizon of the Inceptisol exhibited a CEC of 12 meq/100 g even though its organic matter and clay contents were only 0.3 and 13%, respectively. High solubility of $CaCO_3$ in NH_4OAc solutions, even at neutral pH, has been reported in the soil literature (74). It appears that solubilities of other compounds, such as hydrous Mg silicate ($H_4Mg_3Si_2O_9$) present in serpentine, may be high enough to interfere with the CEC determination.

The possibility of having extracted nonexchangeable cations complicates the interpretation of base saturation data. The Inceptisol showed high base saturation values. The Oxisol had base saturations of 49 and 48% for the 20-50 and 50-125 cm horizons, respectively, which constituted the Oxic horizon. Martini (236) reported base saturations ranging from 10 to 30% for 25 acid Oxisols in Costa Rica. The Entisol and Spodosol had base saturations of 27 and 30%, respectively.

Clay Mineralogy

X-ray diffraction patterns of the clay fraction, less than 0.002-mm size, from the experimental soils are shown in Fig. 2 through 4 and summarized in Table 44. Clay samples were saturated with Mg and K ions. According to Jackson (186), the main purpose for saturating a clay sample with K ion is to test the clay for closure of the montmorillonite and vermiculite interlayers while permitting the chlorite minerals to remain expanded.

The main clay constituent of the Oxisol (Fig. 2) was kaolinite as indicated by strong 7.25 (first order) and 3.57 Å (second order) diffraction peaks. The presence of gibbsite was suggested by weak and broad peaks corresponding to a 4.80 Å d/n spacing. A 14.2 Å diffraction peak in both K- and Mg-saturated samples suggested the presence of some Al-interlayered vermiculite. Quartz was revealed by a medium-intensity 3.35 Å peak. There were only small differences between K- and Mg-saturated specimens; a few more lines appeared in patterns of Mg-saturated clays, but peaks of K-saturated samples were better developed than those with Mg. Samples from different horizons exhibited similar X-ray patterns. The weakly developed 4.80 Å peak from the surface layer of the Oxisol disappeared in samples from underlying horizons.

The X-ray patterns for the Inceptisol (Fig. 3) showed also the

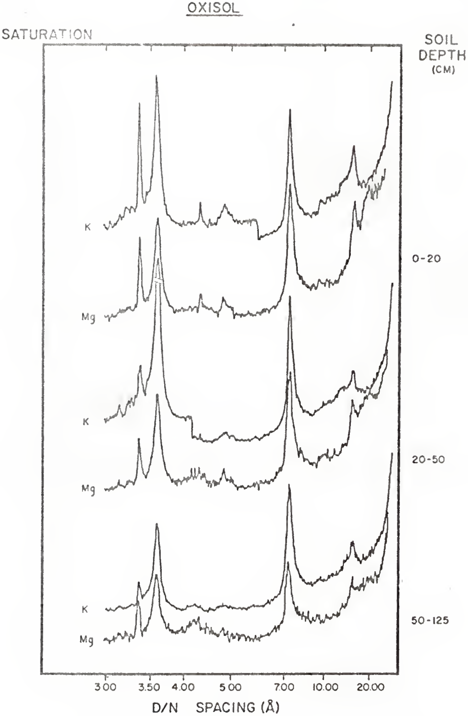

Fig. 2. X-ray diffraction patterns of K- and Mg-saturated clay samples from an Oxisol.

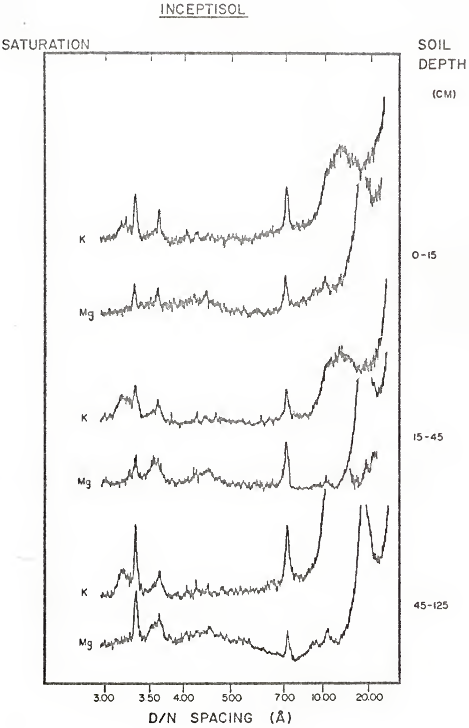

Fig. 3. X-ray diffraction patterns of K- and Mg-saturated clay samples from an Inceptisol.

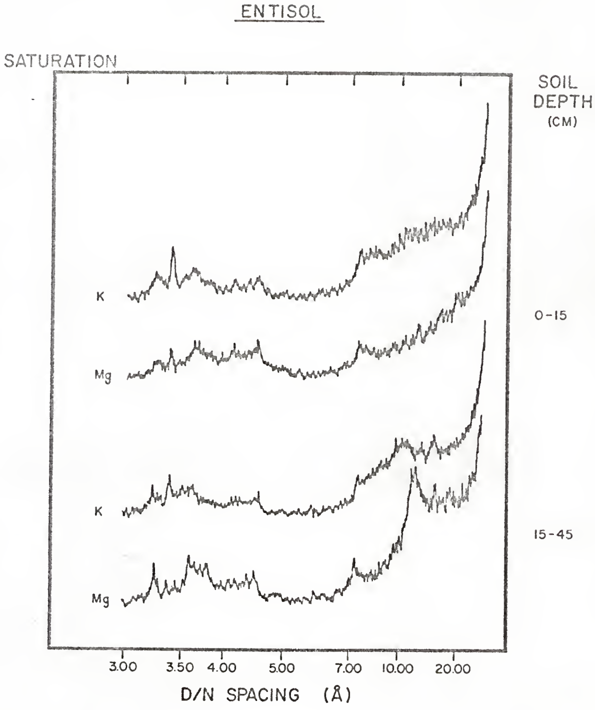

Fig. 4. X-ray diffraction patterns of K- and Mg-saturated clay samples from an Entisol.

predominance of kaolinite (7.25 and 3.57 Å). Quartz peaks at 3.35 Å were of relatively strong intensity in this soil. A 19.20 Å peak from K-saturated specimens may have been produced by a random mixture of 10 and 17.7 Å clays.

The X-ray patterns for the Entisol (Fig. 4) showed the presence of highly weathered, poorly crystalline materials; feldspars were indicated by peaks in the 3.21 and 3.28 Å d-spacing zone.

Soil Fertility Characterization Experiment

Nutrient Deficiencies

An exploratory study aimed at identifying deficient nutrients in three tropical soils was conducted in the greenhouse. The Spodosol (Leon fine sand) was omitted from this study because its fertility status was considered to be well established. Leon fine sand has been reported to be poorly supplied with P, K, Ca, S, Cu, B, and Mo for the growth of legumes (159).

Phaseolus lathyroides (Phasey Bean) was selected as the test plant. This legume is very sensitive to soil nutrient deficiencies; its erect, rapid growth makes it ideal for greenhouse investivation. The nutrients, chemical sources, and rates are shown in Table 5. The plants were harvested 10 weeks after planting.

Phosphorus was the main limiting nutrient in all soils. For the Oxisol, complete fertilization increased dry-matter yields over the control by 208% (Fig. 5). Similar marked increases in yields were obtained for the Entisol (Fig. 6) and Inceptisol (Fig. 7). However, when P was omitted, yields were only 15, 14, and 35% of those obtained from the complete treatment for the Oxisol, Entisol,

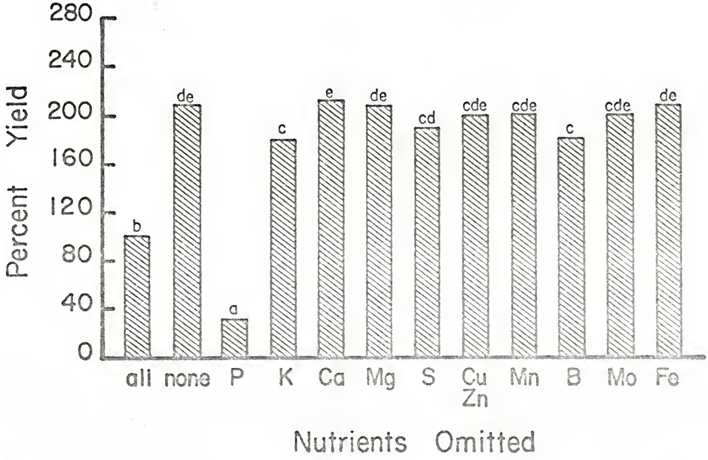

Fig. 5. Effects of various nutrient combinations applied to an Oxisol on oven-dry P. lathyroides herbage yields.

Bars not having a common letter are significantly different at the 5% level.

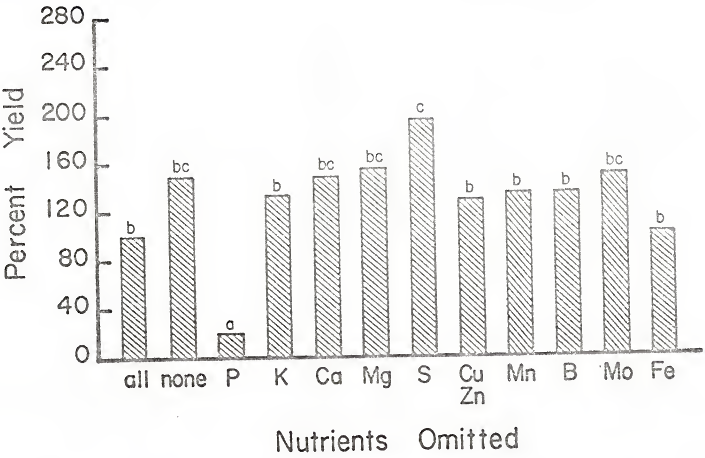

Fig. 6. Effects of various nutrient combinations applied to an Entisol on oven-dry P. lathyroides herbage yields.

Bars not having a common letter are significantly different at the 5% level.

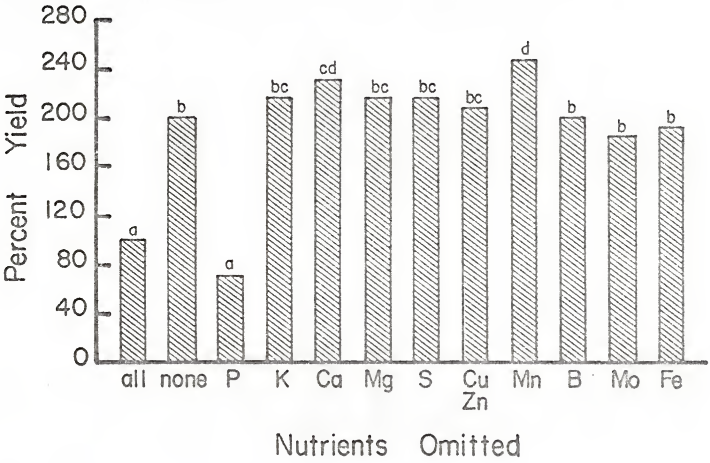

Fig. 7. Effects of various nutrient combinations applied to an Inceptisol on oven-dry P. lathyroides herbage yields.

Bars not having a common letter are significantly different at the 5% level.

and Inceptisol, respectively. These results indicated that the main benefit derived from complete fertilization was due mostly to applied P. Furthermore, application of all nutrients except P to the Oxisol and Entisol significantly depressed dry-matter yields compared with the control. Evidently, applied P was necessary to provide balanced plant nutrition.

Significant yield decreases were also obtained from the Oxisol when K and B were eliminated from the nutrient application; apparently, K and B applications were required for optimum plant growth in this soil. However, one must keep in mind that plant response to any particular element in this experiment was obtained in the presence of other added nutrients. Antagonisms among these elements can complicate interpretations made from the data. For instance, application of Ca or Mg can antagonize K absorption by plants (172); in this experiment, however, omission of Ca and Mg had no effect on yields, nor did they have any effect on K concentration in the plant. Boron is an important element in the nutrition of legumes; Hewitt (172) indicated that B deficiency interfered with sugar translocation in plants. It is easy to visualize how a slow rate of sugar translocation to root nodules could affect N fixation, and consequently reduce plant growth. In addition, Sims and Bingham (332, 333) demonstrated the capacity of hydroxy-Fe and hydroxy-Al compounds, commonly found in Oxisols, to retain B. These conditions may explain the response obtained to B application in this soil.

For the Entisol and Inceptisol, yields were not significantly decreased by omitting any element other than P. Apparently, these soils were well supplied with all nutrients except P.

For the Inceptisol, omission of Ca and Mn produced significant yield increases which suggested the existence of antagonisms between these elements and other essential plant nutrients.

Plant Composition Interactions

Caution must be exercised when interpreting chemical composition data without considering the effect of plant growth. An increment of growth dilutes the concentration of all elements unless a concomitant increase in nutrient absorption occurs. On the other hand, a decrease in growth can concentrate elements in the tissue. The relative lack of plant growth responses obtained in this experiment offered an excellent opportunity to assess the effects of nutrient applications on plant chemical composition in the absence of dry-matter differences.

Data shown in Tables 13 through 16 are summarized in Tables 11 and 12. The concentration of P in the plant changed readily after its omission or addition to the soil. The addition of K, Mn, Cu, Zn, and Fe to the soil did not significantly increase their concentrations in the plant, with the exceptions of K in the Oxisol (Table 11) and Mn in the Inceptisol (Table 12). In some cases, concentrations of Mn, Cu, and Zn in the plant were reduced when they were applied to the soil. Increased dry-matter yields may partially account for some of the observed reductions.

Absorption of Ca by _P. lathyroides_ was apparently increased by practically all elements applied to the Oxisol; i.e., the concentration of Ca in the plant decreased when each element was not applied (Table 11). This effect was not apparent in the Entisol; however, it was significant in the Inceptisol with K, Mn, B, and Fe (Table 12).

Table 11. Effects of omitting an element, applied to an Oxisol and Entisol in combination with all essential plant nutrients except N, on the mineral composition of oven-dry *P. lathyroides* herbage.

Element omitted	Herbage yields	Mineral composition of herbage*							
		P	K	Ca	Mg	Mn	Cu	Zn	Fe
	Net change								
				Oxisol					
None**	+	0	+	+	-	-	0	-	0
P	-	-	-	-	+	+	0	+	0
K	-	0	-	-	+	0	0	0	0
Ca	0	0	0	-	0	+	+	0	0
Mg	0	0	0	-	0	+	0	0	0
S	0	0	0	-	0	0	0	0	0
Cu-Zn	0	0	-	-	0	0	0	0	0
Mn	0	0	0	-	0	0	+	0	0
B	-	0	0	-	0	0	0	0	0
Mo	0	0	-	-	-	0	0	0	0
Fe	0	0	0	-	0	0	0	0	0
				Entisol					
None	0	+	+	-	0	0	-	-	0
P	-	-	-	+	0	0	+	0	0
K	0	0	0	0	0	0	0	0	0
Ca	0	0	0	0	0	0	0	0	0
Mg	0	0	-	0	0	0	0	0	0
S	0	0	0	0	0	0	0	0	+
Cu-Zn	0	0	0	0	0	0	0	0	0
Mn	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0
Mo	0	0	0	0	0	0	0	0	0
Fe	0	0	0	+	0	-	0	0	0

* An increase in concentration is indicated by (+); decrease by (-); no change by (0). Changes were statistically significant at the 5% level.

** This treatment was compared with the control. Other treatments were compared with the "none-omitted" treatment. Numerical data shown in Tables 13 and 14.

Table 12. Effects of omitting an element, applied to an Inceptisol in combination with all essential plant nutrients except N, on the mineral composition of oven-dry P. lathyroides herbage.

		Mineral composition of herbage*							
Element omitted	Herbage yields	P	K	Ca	Mg	Mn	Cu	Zn	Fe
	--------Net change--------								
				Inceptisol					
None**	+	+	+	0	+	+	0	0	0
P	-	-	-	0	-	-	0	0	0
K	0	0	0	-	0	-	0	0	0
Ca	+	0	0	-	-	-	0	0	0
Mg	0	0	0	0	0	-	0	0	0
S	0	0	0	0	0	0	0	0	0
Cu-Zn	0	0	0	0	0	0	0	0	0
Mn	+	0	0	-	-	-	0	0	0
B	0	+	-	-	-	0	0	0	0
Mo	0	0	0	0	0	0	0	0	0
Fe	0	0	0	-	-	-	0	0	0

* An increase in concentration is indicated by (+); a decrease by (-); no change by (0). Changes were statistically significant at the 5% level.

** This treatment was compared with the control. Other treatments were compared with the "none-omitted" treatment. Numerical data shown in Tables 15 and 16.

Table 13. Effects of various nutrient combinations applied to an Oxisol and Entisol on oven-dry yields and P, K, Ca, and Mg concentrations in P. lathyroides herbage.

Nutrients omitted	Herbage yields	Nutrient concentration			
		P	K	Ca	Mg
	g/pot	%			
		Oxisol			
All	1.3 b[*]	0.24 bcd	1.84 b	1.77 b	0.67 e
None[**]	2.7 de	0.23 bcd	3.17 de	2.62 f	0.49 b
Minus P	0.4 a	0.06 a	0.92 a	1.30 a	0.59 d
" K	2.3 c	0.21 bc	2.19 b	2.08 bcde	0.57 cd
" Ca	2.9 e	0.23 bcd	3.13 de	1.90 bc	0.52 bc
" Mg	2.7 de	0.23 bcd	2.82 cd	2.42 e	0.48 b
" S	2.4 cd	0.27 d	3.31 e	3.29 e	0.47 b
" Cu-Zn	2.6 cde	0.19 b	2.69 c	2.24 cde	0.47 b
" Mn	2.6 cde	0.26 cd	3.02 cde	2.28 cde	0.50 bc
" B	2.3 c	0.24 bcd	3.19 de	2.26 cde	0.53 bc
" Mo	2.6 cde	0.19 b	2.65 c	1.95 bcd	0.35 a
" Fe	2.7 de	0.26 cd	3.40 e	2.20 bcde	0.53 bc
		Entisol			
All	1.5 b	0.13 ab	2.42 b	2.67 cde	0.74 c
None	2.2 bc	0.22 c	4.25 d	2.23 ab	0.61 abc
Minus P	0.3 a	0.07 a	1.37 a	2.74 de	0.67 abc
" K	2.0 b	0.20 bc	3.88 cd	2.35 abc	0.64 abc
" Ca	2.2 bc	0.18 bc	3.62 cd	2.00 a	0.60 abc
" Mg	2.3 bc	0.19 bc	3.32 c	2.21 ab	0.53 a
" S	2.9 c	0.22 c	3.94 cd	2.41 bcd	0.74 c
" Cu-Zn	1.9 b	0.18 bc	3.92 cd	2.35 abc	0.62 abc
" Mn	2.0 b	0.21 c	3.13 cd	2.52 bcde	0.61 ab
" B	2.0 b	0.24 c	4.23 d	2.47 bcde	0.63 abc
" Mo	2.2 bc	0.19 bc	3.68 cd	2.24 ab	0.55 ab
" Fe	1.5 b	0.22 c	3.91 cd	2.81 e	0.68 bc

[*] Numbers within vertical columns, within soil groups, not followed by common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 47.

[**] Nutrients applied at rates specified in Table 5 except for the nutrient omitted.

Table 14. Effects of various nutrient combinations applied to an Oxisol and Entisol on Mn, Cu, Zn, and Fe concentrations in oven-dry P. lathyroides herbage.

Nutrients omitted	Nutrient concentrations			
	Mn	Cu	Zn	Fe
	ppm			
	Oxisol			
All	1,110 f*	5 a	92 c	444 a
None**	145 ab	5 a	50 a	238 a
Minus P	787 e	6 ab	69 ab	325 a
" K	176 abcd	6 ab	51 a	233 a
" Ca	226 d	9 c	48 a	244 a
" Mg	218 cd	6 a	45 a	232 a
" S	165 abc	5 a	50 a	215 a
" Cu-Zn	161 abc	5 a	24 a	201 a
" Mn	199 bcd	8 bc	49 a	265 a
" B	188 abcd	7 ab	43 a	232 a
" Mo	136 a	7 ab	45 a	253 a
" Fe	179 abcd	7 ab	44 a	247 a
	Entisol			
All	204 abc	13 c	125 c	227 a
None	271 bcd	5 a	57 ab	232 a
Minus P	283 cd	9 bc	70 b	281 a
" K	291 cd	5 a	46 a	273 a
" Ca	374 d	5 a	47 a	313 ab
" Mg	251 abc	6 ab	46 a	234 a
" S	244 abc	7 ab	45 a	509 b
" Cu-Zn	239 abc	5 a	39 a	298 a
" Mn	252 abc	7 ab	44 a	339 ab
" B	231 abc	6 ab	52 ab	310 ab
" Mo	183 ab	5 a	42 a	263 a
" Fe	178 a	6 ab	54 ab	347 ab

* Numbers within vertical columns, within soil groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 48.

** Nutrients applied at rates specified in Table 5 except for the nutrient omitted.

Table 15. Effects of various nutrients combinations applied to an Inceptisol on oven-dry yields and P, K, Ca, and Mg concentrations in P. lathyroides herbage and roots.

Nutrients omitted	Yields	Nutrient concentrations			
		P	K	Ca	Mg
	g/pot	---	%	---	---
		Herbage			
All	1.3 a*	0.08 a	2.51 ab	1.07 d	1.29 bcd
None**	2.6 b	0.19 bc	3.44 cd	1.03 d	1.46 e
Minus P	0.9 a	0.08 a	1.71 a	0.95 bcd	1.28 bc
" K	2.8 bc	0.19 bc	2.83 bc	0.86 ab	1.31 bcde
" Ca	3.0 cd	0.19 bc	3.94 d	0.88 ab	1.27 bc
" Mg	2.8 bc	0.21 cd	3.54 cd	1.03 d	1.45 de
" S	2.8 bc	0.20 bcd	3.54 cd	0.99 cd	1.47 e
" Cu-Zn	2.7 bc	0.21 cd	3.61 cd	0.99 cd	1.46 e
" Mn	3.2 d	0.18 bc	3.24 bc	0.78 a	1.09 a
" B	2.6 b	0.23 d	3.28 bc	0.83 ab	1.18 ab
" Mo	2.4 b	0.19 bc	3.86 d	1.00 cd	1.41 cde
		Roots			
All	0.5 a	0.07 a	1.76 ab	0.80 g	0.60 bc
None	0.8 bc	0.13 c	2.43 ef	0.49 cde	0.63 bcd
Minus P	0.5 a	0.05 a	2.67 f	0.31 a	1.05 f
" K	0.8 bc	0.13 c	1.92 bc	0.48 cd	0.49 ab
" Ca	0.8 bc	0.14 c	2.19 d	0.42 bc	0.57 bc
" Mg	0.8 bc	0.14 c	2.58 f	0.54 def	0.72 cde
" S	0.8 bc	0.13 c	2.22 de	0.50 cde	0.63 bcd
" Cu-Zn	0.8 bc	0.17 de	2.63 f	0.51 de	0.76 de
" Mn	1.0 d	0.10 b	1.60 a	0.37 ab	0.38 a
" B	0.7 b	0.14 c	2.12 cd	0.60 f	0.71 cde
" Mo	0.8 bc	0.19 e	2.54 f	0.57 f	0.79 e
" Fe	0.9 cd	0.15 cd	2.04 cd	0.42 bc	0.58 bc

* Numbers within vertical columns, within herbage or root groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 49.

** Nutrients applied at rates specified in Table 5 except for the nutrient omitted.

Table 16. Effects of various nutrient combinations applied to an Inceptisol on Mn, Cu, Zn, and Fe concentrations in oven-dry *P. lathyroides* herbage and roots.

Nutrients omitted	Nutrient concentrations			
	Mn	Cu	Zn	Fe
	ppm			
		Herbage		
All	85 a[*]	4 a	51 a	219 a
None[**]	156 cd	4 a	59 a	265 a
Minus P	69 a	4 a	60 a	255 a
" K	127 b	3 a	45 a	270 a
" Ca	123 b	3 a	56 a	257 a
" Mg	124 b	4 a	55 a	264 a
" S	138 bc	3 a	64 a	285 a
" Cu-Zn	144 bc	3 a	49 a	269 a
" Mn	117 b	4 a	54 a	383 a
" B	143 bc	4 a	58 a	374 a
" Mo	180 d	4 a	51 a	328 a
" Fe	125 b	4 a	63 a	197 a
		Roots		
All	54 cd	5 bcd	71 cd	939 ef
None	50 bc	6 cd	40 ab	542 abc
Minus P	89 f	5 bcd	82 d	800 bcdef
" K	31 a	6 cd	24 a	321 a
" Ca	40 ab	3 ab	28 a	527 ab
" Mg	51 bc	2 a	60 bcd	832 def
" S	60 cde	5 bcd	42 abc	819 cdef
" Cu-Zn	70 ef	6 cd	38 ab	1,038 e
" Mn	33 a	4 bc	35 ab	669 bcde
" B	81 fg	4 bc	27 a	819 cdef
" Mo	59 cde	7 d	28 a	862 def
" Fe	65 de	4 bc	63 bcd	604 bcd

[*] Numbers within soil columns, within herbage and root groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 50.

[**] Nutrients applied at rates specified in Table 5 except for the nutrient omitted.

Available Mn in the Oxisol apparently was very high since plant tops from the unfertilized soil contained as much as 1,110 ppm of Mn (Table 14); this is well above the toxicity threshold concentration of 840 ppm reported by Andrew and Hegarty (14) for _P. lathyroides_. Phosphorus appeared to have the greatest effect on reducing Mn concentration in the plant, partially due to a dilution effect. According to Hewitt (172), heavy metals such as Cu, Zn, and Fe, and probably Ca and Mg, can reduce Mn absorption by some plants. The Mn concentrations in plants from the Entisol and Inceptisol were within normal range.

Phosphorus had a marked effect on the K concentration in the plant (Fig. 8). This effect was consistent for all three soils studied. When P was not applied, the concentrations of K in _P. lathyroides_, compared with the complete fertilization treatment, were reduced 2.25, 2.88, and 1.73% for the Oxisol, Entisol, and Inceptisol, respectively. One possible explanation for the effect of applied P on K absorption could be a poorly developed root system, and consequently poor nutrient absorption, as a consequence of P deficiency. However, the effect of applied P on absorption of other cations was significant only for Ca for the Oxisol, and Mg and Mn for the Inceptisol (Tables 11 and 12); these effects, however, were not so marked and consistent as those involving K. One factor complicating the interpretation of data from this experiment is that Cu, Zn, Mn, and Fe were applied in chelated forms (Table 5); the addition of chelating compounds increased the number of possible interactions among components of the fertilizer mixture. Andrew and Robins (17) reported that increased P supply reduced K concentrations in some

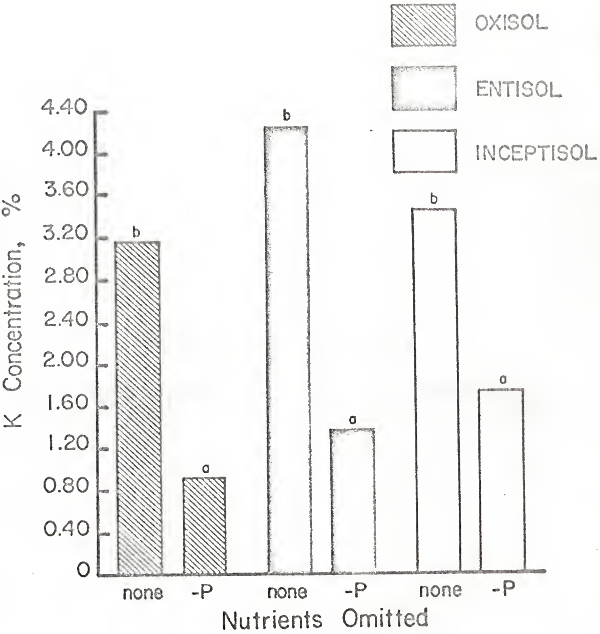

Fig. 8. Effects of P on K concentrations in oven-dry *P. lathyroides* herbage when applied to three tropical soils in combination with all essential plant nutrients except N.

Bars within soil groups not having a common letter are significantly different at the 5% level.

tropical legumes; however, these authors also indicated that the effect of P on cation uptake by legumes was a function of soil, P source, and plant species.

Plant Growth-Plant Composition Relationships

Andrew and co-workers (12, 14, 15, 16, 17, 18, 19, 20) have studied the mineral nutrition of several pasture legumes in Australia; they attempted to establish critical percentages of various elements in the tops of plants. Andrew and Robins (16) reported critical herbage P concentrations of 0.20% for *P. lathyroides*, 0.24% for Siratro, 0.17% for *S. humilis*, 0.16% for *Centrosema*, 0.23% for *Glycine javanica*, 0.17% for *Lotononis bainesii*, 0.24% for *Medicago sativa*, 0.23% for *Desmodium uncinatum*, 0.22% for *Desmodium intortum*, and 0.25% for *Vigna luteola*, at pre-flowering stage. Andrew (12) gave 0.23% P as the critical concentration for *T. repens* var. Irrigation White. Phosphorus concentrations in *P. lathyroides* herbage from the control were 0.24% for the Oxisol, 0.13% for the Entisol, and 0.08% for the Inceptisol (Tables 13 and 15). These values, with the exception of that for the Oxisol, were lower than the critical concentration of 0.20% P reported by Andrew and Robins (16) for the same legume. Plant growth responses to applied P were highly significant for all three soils (Fig. 5 through 7); 150 ppm of applied P (Table 5) resulted in P concentrations in plant tops of 0.19 to 0.22% (Tables 13 and 15).

Andrew and Robins (18) cited critical herbage K concentrations, at pre-flowering stage, of 0.75% for *P. lathyroides* and Siratro, 0.80% for *Desmodium intortum*, 0.72% for *Desmodium uncinatum*, 0.60% for *S. humilis*, 0.90% for *Lotononis bainesii*, 0.75% for *Centrosema*, 0.80%

for Glycine javanica, 1.2% for Medicago sativa, and 1.0% for Medicago truncatula, T. repens, and Trifolium fragiferum. Andrew (12) reported a critical K concentration for T. repens var. Irrigation White of 1.1%. Gammon and Blue (141) reported 2.0% K as critical value for T. repens in sandy soils of Florida.

Potassium concentrations in P. lathyroides ranged from 0.92 to 3.40% for the Oxisol, from 1.37 to 4.25% for the Entisol, and from 1.71 to 3.94% for the Inceptisol (Tables 13 and 15). All these values exceeded the critical K concentration of 0.75% cited by Andrew and Robins (18). However, a significant plant growth response was obtained to 150 ppm of K applied to the Oxisol even though the K concentration in plant tops from the unfertilized soil was 1.84%. One must keep in mind, however, that critical nutrient concentrations are likely to vary for soils in which the nutrient deficiency is complicated by other factors such as antagonistic or synergistic interactions. Smith (335) explained that antagonisms among nutrients may be caused by three general processes, i.e., competition in absorption, competition in translocation, and interference in utilization at the point of destination. Interference with translocation or utilization would be expected to increase the minimum concentration of an element in the plant necessary for optimum nutrition.

Andrew (12) reported a critical Ca concentration of 1.0% for T. repens herbage. Andrew and Norris (15) compared the responses of five tropical and four temperate pasture legumes to lime. They stated that the effect of $CaCO_3$ added to the soil was primarily one of Ca nutrition of the species. Although these authors did not cite critical Ca percentages, it was possible to calculate them from their data.

These concentrations were 1.55% for Desmodium uncinatum, 1.75% for Stylosanthes bojerii, 1.81% for Medicago sativa, 1.83% for Indigofera spicata, 1.37% for P. lathyroides, 1.40% for Trifolium fragiferum, 1.35% for Centrosema, 1.98% for Medicago tribuloides, and 1.33% for T. repens.

Calcium concentrations in P. lathyroides herbage ranged from 1.30 to 2.62% for the Oxisol (Table 13), from 2.00 to 2.81% for the Entisol (Table 13), and from 0.83 to 1.07% for the Inceptisol (Table 15). These values were generally higher than 1.37%, calculated as critical Ca concentration for P. lathyroides (15). The only exceptions were the relatively low Ca concentrations in plants from the Inceptisol which were well below 1.37%. These low Ca concentrations were probably induced by the high Mg content in the Inceptisol (Table 9). Application of 200 ppm of $CaCO_3$, however, did not affect dry-matter yields from any of the soils.

Magnesium concentrations in plant tops ranged from 0.35 to 0.67% for the Oxisol, from 0.53 to 0.74% for the Entisol, and from 1.09 to 1.47% for the Inceptisol (Tables 13 and 15); Mg concentrations from the Inceptisol reflected the serpentine origin of this soil. Applications of Mg to all three soils had no significant effects on plant growth. Embleton (114) listed Mg concentrations ranging from 0.10 to 0.35% for numerous plants showing Mg deficiency symptoms.

Manganese concentrations in plant tops ranged from 136 to 1,110 ppm for the Oxisol, from 178 to 347 ppm for the Entisol, and from 69 to 180 ppm for the Inceptisol (Tables 14 and 16). These Mn concentrations were above the range of 10 to 25 ppm reported by Labanauskas (209) for numerous plants showing Mn deficiency. Applications of Mn to all three soils had no significant effects on plant growth. In the Oxisol, plants from two treatments, i.e., the control and that with all nutrients applied except P, had Mn concentrations of 1,110 and 787 ppm, respectively. These high values suggest toxic effects of Mn on plant growth; the threshold concentration for Mn toxicity for _P. lathyroides_ was listed as 840 ppm in Table 1.

Andrew and Thorne (20) considered that for several tropical and temperate legumes growing in Australia, Cu concentrations higher than 5 ppm in the plant were satisfactory, while 4 to 5 ppm were marginal and less than 4 ppm indicated Cu deficiency. Copper concentrations in _P. lathyroides_ herbage (Tables 14 and 16) were usually equal or higher than 5 ppm with the exception of the Inceptisol. Zinc concentrations in plant tops ranged from 42 to 92 ppm for the Oxisol, 39 to 125 ppm for the Entisol, and 45 to 64 ppm for the Inceptisol (Tables 14 and 16). Plant response to Zn application was not significant for any of the soils. Chapman (76) listed Zn deficiency levels of less than 20 to 25 ppm for a variety of plants.

Iron concentrations in plant tops showed great experimental variability which prevented some trends to attain statistical significance. Iron concentrations in the herbage varied from 201 to 444 ppm for the Oxisol, from 227 to 509 ppm for the Entisol, and from 197 to 383 ppm for the Inceptisol (Tables 14 and 16). Wallihan (376) listed Fe concentrations of 10 to 70 ppm for numerous plants showing deficiency symptoms. Levels of Fe in plants from this experiment were above critical values.

Plant Response-Soil Test Relationships

The Oxisol was described earlier as having a relatively small supply of exchangeable K and greatly unbalanced Mg to K ratios (Tables 9 and 10). The decrease in growth observed when K was not applied supported the conclusion derived from the soil test. However, the Inceptisol, with Mg to K ratios as large as 140, did not respond significantly to the addition of K, nor did the Entisol respond to Mg application with a Mg to K ratio of 1.5. These facts suggest that nutrient ratios are difficult to interpret and caution must be exercised before drawing conclusions on that basis. It is possible that soil nutrient ratios may affect plant mineral requirements under some soil conditions. Research in this field should be aimed at identifying these soil conditions. Furthermore, soil tests for exchangeable K, Ca, and Mg may need improvement. Unfavorable Ca/Mg, Mg/K, or (Ca + Mg)/K ratios generally occur in soils with high contents of K, Ca, or Mg as carbonates, sulfates, and silicates; the solubilities of these compounds in the extracting solutions (for example, NH_4OAc at all commonly used pH values) are high and generally lead to considerable analytical errors (74).

Low test results for soil P, extracted with Mehlich's and Bray's reagents, were consistent with the large responses obtained to applied P for all soils.

Liming Experiments

Experiment 1

This experiment was conducted to study plant response to liming as affected by applied P, soil group, and plant species. The soils used were an Oxisol collected from the region of Lake Izabal, Guatemala, and a Spodosol (Leon fine sand) obtained from the Beef Research Unit, University of Florida, Gainesville, Florida. One tropical and one temperate legume, i.e., Centrosema (Centrosema pubescens Benth.) and T. repens (Trifolium repens L.) were used to compare their responses to liming. Lime rates were 0, 600, 1,200, and 1,800 ppm of reagent grade $CaCO_3$. Phosphorus rates were 0, 25, 50, and 75 ppm. All pots received a minimal basal fertilization including K, Mg, S, Cu, Zn, Mn, B, and Mo. Plant tops and roots were harvested 18 weeks after planting for Centrosema and 14 weeks for T. repens. The experiment was replanted to Centrosema and plant tops were harvested 18 weeks later.

Application of 1,800 ppm of $CaCO_3$ raised the pH from 5.6 to 6.8 for the Oxisol, and from 4.9 to 6.5 for the Spodosol (Table 45). Applied P increased pH slightly, particularly for the Spodosol. These pH values were slightly lower than expected from lime requirement determinations (Table 46). This would be expected since lime reacts slowly with the soil under greenhouse or field conditions.

First planting

Plant growth.--For the Oxisol, the beneficial effect of lime on oven-dry Centrosema and T. repens herbage yields was limited to the first rate, 600 ppm of $CaCO_3$ (Fig. 9 and 10, Table 51). The effect of this lime rate on plant growth depended on P rates and legume species. For example, without applied P the effect was small; at a rate of 25 ppm of P, only Centrosema yields increased; at higher P rates, 50 and 75 ppm, lime increased yields of T. repens as well. Lime rates higher than 600 ppm of $CaCO_3$ depressed yields significantly. But again, the magnitude of these yield depressions depended on P rates and legume species. At lower P rates, 0 and 25 ppm, the negative effect of lime was very marked, particularly for Centrosema. However,

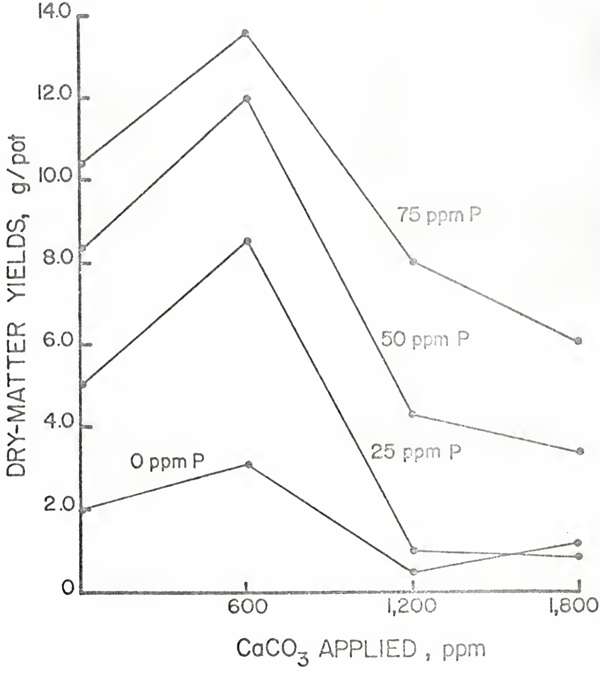

Fig. 9. Effects of lime and P applied to an Oxisol on oven-dry Centrosema herbage yields from the first planting.

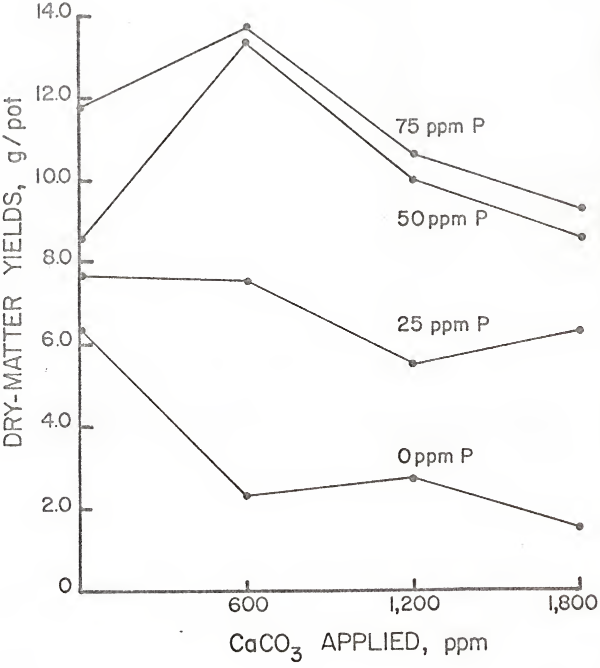

Fig. 10. Effects of lime and P applied to an Oxisol on oven-dry T. repens herbage yields.

at a P rate of 75 ppm, the magnitude of lime-induced yield depressions significantly decreased for both legumes. Both species were adversely affected by excessive liming, particularly with low P rates; however, T. repens yields were depressed to a lesser degree. For example, with 50 ppm of applied P, Centrosema and T. repens yields were reduced 64 and 25%, respectively, when lime rates were increased from 600 to 1,200 ppm of $CaCO_3$.

Trifolium repens failed to grow and Centrosema grew very little on the unlimed, Ca deficient Spodosol (Leon fine sand). In this soil, both legumes responded well to lime through 1,200 ppm of $CaCO_3$ (Fig. 11 and Table 51); thereafter, lime did not significantly affect dry-matter yields. Data in Table 51 show that significant lime-induced yield depressions from this soil occurred only when 1,800 ppm of $CaCO_3$ were applied without P.

The effects of lime and P on dry-matter yields were all highly significant (Table 52). Cubic regression terms for both legumes in the Oxisol, and Centrosema in the Spodosol, were highly significant. The evidence of such relationships is clear from an examination of Fig. 9 through 11. For example, Centrosema and T. repens yield responses to lime from the Oxisol showed three slopes, i.e., yields generally increased from lime level one to level two with a sharp drop for the third level and a distinct, less steep, drop for the fourth level (Fig. 9 and 10). The effect of lime on T. repens yields from the Spodosol could be best described by a combination of linear and quadratic regression terms only (Table 52). It can be noted (Fig. 11) that the yield response of T. repens from the Spodosol had two slopes between lime level one and level three; this made the

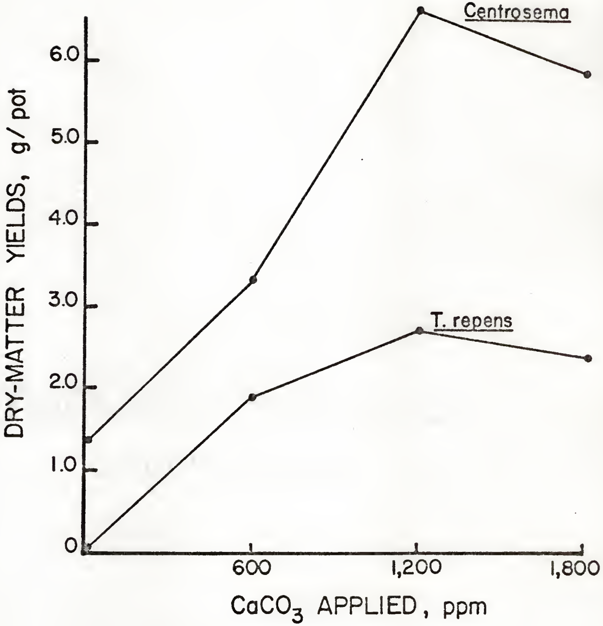

Fig. 11. Effects of lime and P applied to a Spodosol on oven-dry Centrosema and T. repens herbage yields.

quadratic term significant. The cubic regression term was not significant because although there was a slight yield decrease between lime level three and level four, this effect was not significant. In general terms, this was the reasoning behind interpretations made of statistical significance of regression terms shown in analysis of variance tables.

In general, root yields showed similar treatment effects as herbage yields (Table 17). For example, oven-dry Centrosema root yields from the Oxisol increased from lime level one to level two; this increase was more marked with increased rates of P. Furthermore, there was a sharp decrease in root yields from lime level two to level three; this decrease was less marked as P rates increased.

Plant composition.--Nitrogen concentrations in Centrosema herbage from the Oxisol were high at all lime and P rates (Fig. 12). Evidently, neither lime nor P effects were related to N deficiency conditions in this soil. It appears that differences in N concentrations were related to differences in dry-matter production rather than direct treatment effects on N fixation or absorption. Effects of lime and P on N concentrations (Table 53) in T. repens for the Oxisol, and in both legumes for the Spodosol, were similar to those shown in Fig. 12 for Centrosema. For the Oxisol, N concentrations ranged from 2.80 to 4.34% for Centrosema and from 3.50 to 4.77% for T. repens. For the Spodosol, N concentrations ranged from 1.91 to 3.42% for Centrosema and from 1.83 to 3.91% for T. repens. Effects of lime and applied P on N contents in legume herbage were very marked (Fig. 12 and Table 54). These effects were apparently caused by differences in dry-matter production among treatments.

Table 17. Effects of lime and P applied to an Oxisol and Spodosol on oven-dry Centrosema and T. repens root yields from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Roots, g/pot				
	Oxisol (Centrosema)				
0	0.8 ab*	1.0 abc	1.6 bcd	1.4 abcd	1.2
600	1.0 abc	2.3 cde	3.6 ef	4.1 f	2.8
1,200	0.2 a	0.2 a	0.6 ab	2.5 de	0.9
1,800	0.5 ab	0.3 ab	0.8 ab	1.4 abcd	0.8
Mean	0.6	1.0	1.7	2.4	1.4
	Oxisol (T. repens)				
0	2.4 bc	3.9 defg	4.9 g	5.1 g	4.1
600	3.2 bcde	5.2 g	7.7 fg	11.4 h	6.9
1,200	1.9 ab	2.8 bcd	4.6 efg	5.0 g	3.6
1,800	0.8 a	3.4 cde	4.0 defg	4.9 g	3.3
Mean	2.1	3.8	5.3	6.6	4.4
	Spodosol (Centrosema)				
0	0.3	0.5	0.2	0.7	0.4 m
600	1.3	1.2	1.4	1.2	1.3 m
1,200	1.7	1.2	1.2	1.4	1.4 n
1,800	1.0	1.2	1.2	1.4	1.6 n
Mean	1.1 a	1.0 a	1.0 a	1.2 a	1.1
	Spodosol (T. repens)				
0	0.0	0.0	0.0	0.0	0.0
600	1.1 ab	2.1 cdef	1.7 bcde	1.3 abc	1.6
1,200	1.6 bcd	3.7 g	2.2 def	2.4 def	2.5
1,800	0.6 a	2.5 ef	2.9 fg	2.6 f	2.2
Mean	1.1	2.8	2.3	2.1	2.1

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-h and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 76.

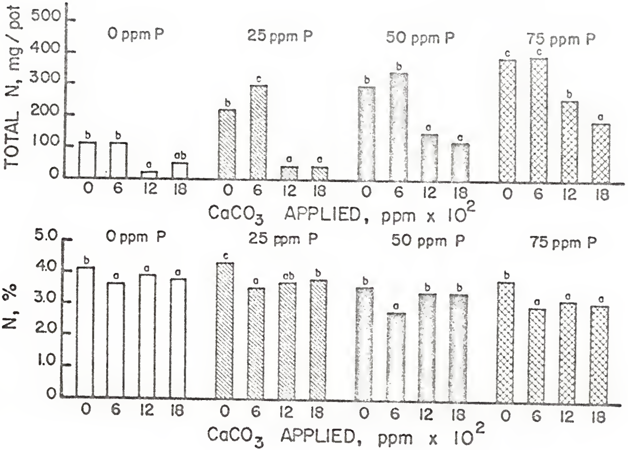

Fig. 12. Effects of lime and P applied to an Oxisol on N concentrations and contents in oven-dry Centrosema herbage from the first planting.

Bars not having a common letter, within P groups, are significantly different at the 5% level.

For herbage P concentrations (Table 18), the interaction between lime and P was not significant for any soil-legume combination except for T. repens from the Spodosol (Table 55). The effect of lime on herbage P concentrations was not significant except for Centrosema when 1,200 ppm of $CaCO_3$ were applied to the Oxisol (Table 18). In contrast with plant tops, there were significant interactions between lime and P on root P concentrations for all soil-legume combinations (Table 56). Furthermore, 1,800 ppm of $CaCO_3$ generally decreased P concentrations in roots when applied in combination with P rates of 50 ppm or higher (Table 19).

Phosphorus concentrations in plant tops (Table 18) and roots (Table 19) were similar for both soils and legumes when P was not applied. With increased P rates, however, herbage and root P concentrations were higher for the Spodosol than for the Oxisol. Phosphorus concentrations in plant tops from the Oxisol were generally lower than critical concentrations of 0.16 and 0.23% cited by Andrew and Robins (16) for Centrosema and Andrew (12) for T. repens, respectively. For the Spodosol, P concentrations in plant tops were below critical percentages only when P was not applied.

Potassium concentrations in plant tops (Table 20) were generally related to dry-matter yields. Therefore, changes in K concentration can be explained as due to dilution or concentration effects. For the Oxisol, K concentrations ranged from 1.00 to 2.10% for Centrosema and from 1.77 to 3.85% for T. repens. For the Spodosol, K in the same legumes ranged from 1.45 to 3.07% and from 3.90 to 4.41% K, respectively. Potassium concentrations in plant tops from the Spodosol were much higher than from the Oxisol. This was probably due to a

Table 18. Effects of lime and P applied to an Oxisol and Spodosol on P concentrations in oven-dry *Centrosema* and *T. repens* herbage from the first planting.

CaCO$_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Herbage P, %				
	Oxisol (*Centrosema*)				
0	0.09	0.11	0.14	0.16	0.13 m
600	0.11	0.12	0.15	0.18	0.14 m
1,200	0.14	0.18	0.21	0.24	0.19 n
1,800	0.12	0.10	0.12	0.20	0.14 m
Mean	0.12 a*	0.13 a	0.16 ab	0.20 b	0.15
	Oxisol (*T. repens*)				
0	0.12	0.13	0.18	0.23	0.17 m
600	0.11	0.13	0.14	0.20	0.15 m
1,200	0.09	0.15	0.20	0.26	0.18 m
1,800	0.12	0.13	0.16	0.23	0.16 m
Mean	0.11 a	0.14 a	0.17 ab	0.23 b	0.17
	Spodosol (*Centrosema*)				
0	0.12	0.40	0.44	0.96	0.48 m
600	0.15	0.47	0.48	0.88	0.50 m
1,200	0.17	0.48	0.48	0.64	0.44 m
1,800	0.16	0.40	0.42	0.72	0.43 m
Mean	0.15 a	0.44 b	0.46 b	0.80 c	0.46
	Spodosol (*T. repens*)				
0	-**	-	-	-	-
600	0.12 a	0.28 d	0.76 h	0.80 h	0.49
1,200	0.14 ab	0.24 cd	0.64 fg	0.72 gh	0.44
1,800	0.16 abc	0.22 bcd	0.56 ef	0.52 e	0.37
Mean	0.14	0.25	0.65	0.68	0.43

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-h and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 55.

** Insufficient plant material for chemical analysis.

Table 19. Effects of lime and P applied to an Oxisol and Spodosol on P concentrations in oven-dry Centrosema and T. repens roots from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Root P, %				
	Oxisol (Centrosema)				
0	0.10 a*	0.13 abc	0.15 bcd	0.18 d	0.14
600	0.17 cd	0.13 abc	0.17 cd	0.17 cd	0.16
1,200	0.11 ab	0.12 ab	0.18 d	0.17 cd	0.14
1,800	0.11 ab	0.10 a	0.10 a	0.10 a	0.10
Mean	0.12	0.12	0.15	0.16	0.14
	Oxisol (T. repens)				
0	0.15 abc	0.15 abc	0.22 de	0.20 cd	0.18
600	0.14 ab	0.15 abc	0.19 bcd	0.27 e	0.19
1,200	0.14 ab	0.19 bcd	0.22 de	0.15 abc	0.18
1,800	0.12 a	0.13 a	0.13 a	0.15 abc	0.13
Mean	0.14	0.16	0.19	0.19	0.17
	Spodosol (Centrosema)				
0	0.11 a	0.22 bc	0.31 de	0.38 fg	0.26
600	0.12 a	0.29 de	0.32 def	0.44 gh	0.29
1,200	0.17 ab	0.29 de	0.33 def	0.47 h	0.32
1,800	0.17 ab	0.28 cd	0.38 fg	0.35 ef	0.30
Mean	0.14	0.27	0.34	0.41	0.29
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	0.12 a	0.25 b	0.50 e	0.59 f	0.36
1,200	0.14 a	0.23 b	0.35 d	0.60 f	0.33
1,800	0.13 a	0.22 b	0.30 c	0.37 d	0.26
Mean	0.13	0.23	0.38	0.52	0.32

* Numbers within soil-legume groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 56.

** Insufficient plant material for chemical analysis.

Table 20. Effects of lime and P applied to an Oxisol and Spodosol on K concentrations in oven-dry *Centrosema* and *T. repens* herbage from the first planting.

CaCO$_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Herbage K, %				
		Oxisol (Centrosema)			
0	2.10 i*	1.71 h	1.45 efg	1.48 fgh	1.68
600	1.35 bcdef	1.15 abc	1.20 abcd	1.18 abcd	1.22
1,200	1.70 gh	1.40 cdef	1.43 def	1.00 a	1.38
1,800	1.45 efg	1.30 bcdef	1.31 bcdef	1.10 ab	1.29
Mean	1.65	1.40	1.35	1.19	1.39
		Oxisol (T. repens)			
0	3.38 f	3.85 g	2.40 bc	2.07 ab	2.92
600	2.93 e	3.76 fg	1.85 a	1.77 a	2.58
1,200	2.63 cde	3.77 g	2.61 cde	2.62 cde	2.91
1,800	2.50 cd	3.00 e	2.82 de	2.27 bc	2.64
Mean	2.86	3.60	2.42	2.18	2.76
		Spodosol (Centrosema)			
0	3.07 g	3.00 g	2.27 e	2.53 f	2.72
600	2.26 de	2.14 de	2.03 cd	2.18 de	2.15
1,200	1.79 b	1.85 bc	1.74 b	1.88 bc	1.82
1,800	1.75 b	1.65 ab	1.45 a	1.45 a	1.58
Mean	2.22	2.16	1.87	2.01	2.07
		Spodosol (T. repens)			
0	- **	-	-	-	-
600	4.23	4.01	4.02	4.41	4.17 m
1,200	4.28	4.01	4.08	4.10	4.12 m
1,800	3.93	3.90	4.07	4.18	4.02 m
Mean	4.15 bc	3.97 a	4.06 ab	4.23 c	4.10

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-i and m-n, aresignificantly different at the 5% level. Summaries of the analyses of variance are shown in Table 69.

** Insufficient plant material for chemical analysis.

lower supply of available K in the Oxisol as previously indicated. All K concentrations exceeded critical percentages of 0.75 and 1.1 cited in the literature for Centrosema and T. repens, respectively (12, 18). Potassium concentrations in roots (Table 57) were generally one-half to one-third those in plant tops. For the Oxisol, K concentrations in roots were apparently controlled by dilution or concentration effects related to dry-matter production. For the Spodosol, however, K concentrations in roots increased significantly with increased rates of lime.

Liming invariably increased Ca concentrations in plant tops (Table 21) and roots (Table 58). For the Oxisol, herbage Ca concentrations ranged from 1.59 to 3.10% for Centrosema and from 1.72 to 2.60% for T. repens. These values were higher than critical Ca concentrations of 1.35 and 1.33% for the same legume species, respectively, calculated from data by Andrew and Norris (15). For the Spodosol, Ca concentrations in plant tops ranged from 0.67 to 2.67% for Centrosema and from 1.39 to 2.50% for T. repens. Trifolium repens failed to grow on the unlimed Spodosol, but Centrosema grew to some extent (Fig. 11). Calcium concentrations in Centrosema from the unlimed Spodosol were below critical percentages. Application of P to the Oxisol reduced herbage Ca concentrations for both legumes. These reductions can be explained as due to dilution since dry-matter yields increased simultaneously (Fig. 9 and 10). For the Spodosol, applied P had the opposite effect on Centrosema Ca concentrations, i.e., herbage Ca concentrations increased with increased P rates. For this soil, there was no plant response to applied P beyond the 25 ppm rate, and consequently there was no dilution effect on Ca concentrations.

Table 21. Effects of lime and P applied to an Oxisol and Spodosol on Ca concentrations in oven-dry Centrosema and *T. repens* herbage from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Herbage Ca, %				
	Oxisol (Centrosema)				
0	1.86	1.80	1.74	1.59	1.75 m
600	2.40	2.20	2.10	1.96	2.16 n
1,200	2.74	2.60	2.54	2.40	2.57 o
1,800	3.10	3.00	2.92	2.90	2.98 p
Mean	2.52 b*	2.40 ab	2.32 ab	2.21 a	2.36
	Oxisol (*T. repens*)				
0	2.04	2.00	1.80	1.72	1.89 m
600	2.30	2.20	1.90	1.90	2.08 n
1,200	2.40	2.50	2.20	2.10	2.30 o
1,800	2.60	2.54	2.46	2.36	2.49 p
Mean	2.34 b	2.31 b	2.09 a	2.02 a	2.19
	Spodosol (Centrosema)				
0	0.67	1.05	1.11	1.11	0.98 m
600	1.96	2.08	2.31	2.03	2.09 n
1,200	2.18	2.20	2.52	2.52	2.36 o
1,800	2.56	2.50	2.61	2.67	2.58 p
Mean	1.84 a	1.96 ab	2.14 c	2.08 bc	2.00
	Spodosol (*T. repens*)				
0	-**	-	-	-	-
600	1.81 b	1.39 a	2.04 bcd	2.16 de	1.85
1,200	2.22 def	1.90 bc	2.16 de	2.23 def	2.13
1,800	2.50 f	2.15 cde	2.39 ef	2.35 ef	2.35
Mean	2.18	1.81	2.20	2.25	2.11

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-f and m-p, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 70.

** Insufficient plant material for chemical analysis.

It is also possible that P increased Ca uptake by plants by promoting root development. Calcium concentrations in roots (Table 58) were approximately one-third to one-half those in the herbage (Table 21); however, lime and applied P effects on root Ca concentrations were generally similar to those observed in plant tops.

For the Oxisol, herbage Mg concentrations (Table 22) ranged from 0.30 to 0.49% for *Centrosema* and from 0.50 to 0.78% for *T. repens*. For the Spodosol, Mg concentrations ranged from 0.23 to 0.64% for *Centrosema* and from 0.29 to 0.40% for *T. repens*. There were no unconfounded effects of lime on Mg concentrations; some significant differences occurred, but they can be explained as due to dilution. For the Oxisol, Mg concentrations in *Centrosema* herbage decreased with increased P rates. This effect was confounded with increased dry-matter yields. The decrease in Mg concentration for *T. repens* between 50 and 75 ppm of P was not confounded with yield differences, which indicates that applied P decreased Mg absorption. For the Spodosol, the effect of applied P on Mg concentrations in plant tops was generally confounded with dilution effects. Magnesium concentrations in roots (Table 59) were similar or somewhat lower than in plant tops.

Manganese concentrations in plant tops decreased with increased lime rates (Table 23). The effect of lime on Mn concentrations was generally confounded with growth effects. However, for the Oxisol, differences in herbage Mn between lime level two and level four suggest a negative effect of lime on Mn absorption. For example, herbage Mn concentrations decreased between these lime levels from 98 to 56 ppm for *Centrosema* and from 159 to 84 ppm for *T. repens*. These significant reductions can not be accounted by increases in dry matter.

Table 22. Effects of lime and P applied to an Oxisol and Spodosol on Mg concentrations in oven-dry Centrosema and *T. repens* herbage from the first planting.

$CaCO_3$ applied ppm	P applied, ppm				
	0	25	50	75	Mean
	Herbage Mg, %				
		Oxisol (Centrosema)			
0	0.46	0.44	0.35	0.38	0.41 mn
600	0.48	0.40	0.30	0.35	0.38 m
1,200	0.49	0.46	0.45	0.43	0.46 o
1,800	0.45	0.47	0.44	0.40	0.44 no
Mean	0.47 b*	0.44 b	0.38 a	0.38 a	0.42
		Oxisol (*T. repens*)			
0	0.78	0.65	0.75	0.50	0.67 m
600	0.65	0.60	0.70	0.52	0.62 m
1,200	0.65	0.63	0.73	0.58	0.65 m
1,800	0.63	0.64	0.66	0.64	0.64 m
Mean	0.68 bc	0.63 ab	0.71 c	0.56 a	0.64
		Spodosol (Centrosema)			
0	0.64	0.56	0.50	0.52	0.56 o
600	0.41	0.36	0.36	0.32	0.36 n
1,200	0.30	0.27	0.28	0.29	0.28 m
1,800	0.28	0.27	0.23	0.24	0.26 m
Mean	0.41 b	0.36 a	0.34 a	0.34 a	0.36
		Spodosol (*T. repens*)			
0	-**	-	-	-	-
600	0.40	0.34	0.40	0.40	0.38 n
1,200	0.33	0.32	0.35	0.33	0.33 m
1,800	0.36	0.35	0.30	0.29	0.32 m
Mean	0.36 a	0.34 a	0.35 a	0.34 a	0.34

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-c and m-o, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 71.

** Insufficient plant material for chemical analysis.

Table 23. Effects of lime and P applied to an Oxisol and Spodosol on Mn concentrations in oven-dry Centrosema and T. repens herbage from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Herbage Mn, ppm				
	Oxisol (Centrosema)				
0	150	140	124	130	136 p
600	110	104	80	100	98 o
1,200	90	80	66	60	74 n
1,800	60	60	50	56	56 m
Mean	102 b*	96 b	80 a	86 a	91
	Oxisol (T. repens)				
0	256	210	207	194	217 p
600	180	165	170	120	159 o
1,200	138	110	88	86	106 n
1,800	120	95	70	50	84 m
Mean	174 c	145 b	134 b	112 a	142
	Spodosol (Centrosema)				
0	324 h	293 g	223 ef	214 def	264
600	244 f	243 f	191 d	204 de	220
1,200	75 c	69 bc	66 bc	61 abc	68
1,800	43 ab	35 a	32 a	34 a	36
Mean	172	160	128	128	147
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	173	160	179	173	171 o
1,200	54	58	47	40	50 n
1,800	37	42	31	26	34 m
Mean	88 a	87 a	86 a	80 a	85

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-h and m-p, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 72.

** Insufficient plant material for chemical analysis.

Manganese concentrations in plant tops decreased with increased P rates (Table 23). These effects, however, were confounded with growth effects.

The effects of lime and applied P on root Mn concentrations (Table 60) were similar to those observed for the herbage. Manganese concentrations in plant tops and roots for all treatments were higher than 25 ppm, which is the value generally reported in the literature as critical concentration (209); Mn in herbage and roots was also lower than toxicity threshold concentrations, i.e., 1,600 ppm for _Centrosema_ and 600 for _T. repens_ (14).

Copper concentrations in plant tops (Table 24) were relatively high, particularly for the Spodosol. According to Andrew and Thorne (20), a Cu concentration higher than 5 ppm in plant tops was satisfactory for several legumes in Australia. For the Oxisol, Cu concentrations varied from 6 to 14 ppm for _Centrosema_ and from 5 to 12 ppm for _T. repens_. For the Spodosol, ranges for the same legumes were from 8 to 24 ppm and from 4 to 18 ppm, respectively. Copper concentrations in plant roots (Table 61) were generally higher than in herbage for the Oxisol. Copper concentrations in roots and tops from the Spodosol were similar. Lime apparently had a negative effect on Cu absorption in plants from the Spodosol.

Effects of lime and applied P on herbage Zn concentrations (Table 25) were similar to those observed for Mn. Zinc in the herbage generally decreased markedly with application of 600 ppm of $CaCO_3$; however, this effect was confounded with a simultaneous increase in yields. The effect of applied P on Zn concentrations was similar to that of lime.

Table 24. Effects of lime and P applied to an Oxisol and Spodosol on Cu concentrations in oven-dry *Centrosema* and *T. repens* herbage from the first planting.

$CaCO_3$ applied ppm	P applied, ppm				
	0	25	50	75	Mean
	Herbage Cu, ppm				
	Oxisol (Centrosema)				
0	10	8	8	7	8 m
600	7	11	7	7	8 m
1,200	13	14	8	7	10 m
1,800	10	6	9	9	8 m
Mean	10 a*	10 a	8 a	8 a	8
	Oxisol (T. repens)				
0	9	7	9	8	8 m
600	10	6	8	8	8 m
1,200	9	7	12	8	9 m
1,800	10	8	5	7	8 m
Mean	10 b	7 a	8 ab	8 ab	8
	Spodosol (Centrosema)				
0	20	24	19	20	21 p
600	16	17	17	13	16 o
1,200	12	12	15	11	12 n
1,800	9	8	8	10	9 m
Mean	14 a	15 a	15 a	14 a	14
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	10	16	18	16	15 o
1,200	8	11	10	11	10 n
1,800	4	8	6	6	6 m
Mean	7 a	12 b	11 b	11 b	10

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-b and m-p, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 73.

** Insufficient plant material for chemical analysis.

Table 25. Effects of lime and P applied to an Oxisol and Spodosol on Zn concentrations in oven-dry Centrosema and T. repens herbage from the first planting.

$CaCO_3$ applied ppm	P applied, ppm 0	25	50	75	Mean
	---Herbage Zn, ppm---				
	Oxisol (Centrosema)				
0	180 f*	110 e	50 abc	44 abc	96
600	70 d	50 abc	40 ab	40 ab	50
1,200	60 cd	50 abc	44 abc	34 a	47
1,800	50 abc	56 bcd	50 abc	40 ab	49
Mean	90	66	46	40	60
	Oxisol (T. repens)				
0	80	60	54	48	60 o
600	60	50	44	40	48 n
1,200	48	50	44	40	46 n
1,800	36	36	30	30	33 m
Mean	56 c	49 bc	43 ab	40 a	46
	Spodosol (Centrosema)				
0	318 f	273 e	171 d	188 d	238
600	103 bc	105 c	89 abc	84 abc	95
1,200	77 abc	75 abc	77 abc	73 abc	76
1,800	77 abc	62 a	64 ab	65 abc	67
Mean	144	129	100	102	119
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	125 e	100 d	99 d	94 d	104
1,200	64 c	50 bc	57 c	60 c	58
1,800	61 c	40 ab	34 a	31 a	42
Mean	83	63	63	62	68

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-f and m-o, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 74.

** Insufficient plant material for chemical analysis.

For the Oxisol, herbage Zn concentrations varied from 34 to 180 ppm for Centrosema and from 30 to 80 ppm for T. repens. Higher Zn concentrations invariably occurred on unlimed soils without applied P; lower Zn concentrations generally occurred when 1,800 ppm of $CaCO_3$ and 75 ppm of P were applied. For the Spodosol, Zn concentrations ranged from 62 to 318 ppm for Centrosema and from 31 to 125 ppm for T. repens. Zinc concentrations in Centrosema roots (Table 62) were generally lower than in the herbage but the opposite was true for T. repens. Lime and applied P effects on Zn concentrations in roots were similar to those for plant tops.

For the Oxisol, herbage Fe concentrations varied from 217 to 362 ppm for Centrosema and from 382 to 876 ppm for T. repens (Table 26). For the Spodosol, Fe concentrations in the same legumes ranged from 142 to 257 ppm and from 159 to 257 ppm, respectively. For the Oxisol, Fe concentrations in roots (Table 63) were on the average 10 to 30 times those in plant tops. These high root Fe concentrations were probably due to root contamination by soil. For the Spodosol, Fe concentrations in roots were only 2 to 4 times those in the herbage. The effect of lime on Fe concentrations in plant tops was generally confounded with yield differences.

Accumulation of P and Al in roots of plants growing in media high in Al has been reported in the literature (86, 190, 313, 387). Some investigators (86, 387) have used chemical extractants to show that Al phosphate precipitation sometimes occurs in plant roots. In this investigation, Al concentrations in roots (Table 64), particularly from the Oxisol, were highly variable probably due to root contamination by soil.

Table 26. Effects of lime and P applied to an Oxisol and Spodosol on Fe concentrations in oven-dry Centrosema and T. repens herbage from the first planting.

$CaCO_3$ applied ppm	P applied, ppm				
	0	25	50	75	Mean
	Herbage Fe, ppm				
	Oxisol (Centrosema)				
0	217	304	276	247	261 m
600	335	362	245	218	290 m
1,200	301	351	249	242	286 m
1,800	262	269	333	224	272 m
Mean	279 a*	322 a	276 a	233 a	277
	Oxisol (T. repens)				
0	876 d	589 abc	577 abc	669 bcd	678
600	665 bcd	551 abc	616 bc	507 abc	585
1,200	516 abc	540 abc	595 abc	605 abc	564
1,800	556 abc	449 ab	688 cd	382 a	519
Mean	653	532	619	541	586
	Spodosol (Centrosema)				
0	219	257	215	228	230 o
600	185	215	212	170	196 n
1,200	149	174	177	147	162 m
1,800	127	173	151	142	148 m
Mean	170 a	205 b	189 ab	172 a	184
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	159	188	257	243	212 m
1,200	162	185	183	166	174 m
1,800	213	173	169	159	178 m
Mean	178 a	182 a	203 a	189 a	188

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-d and m-o, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 75.

** Insufficient plant material for chemical analysis.

Second planting

Plant growth.--Application of 600 ppm of $CaCO_3$ to the Oxisol increased Centrosema yields significantly only when P was not applied (Fig. 13). In contrast, yields from the first planting increased with application of 600 ppm of $CaCO_3$ at all P rates (Fig. 9). For the Oxisol, there was a significant interaction between lime and applied P effects on Centrosema dry-matter yields (Table 66). For the unlimed Oxisol, dry-matter yields increased with increased P rates through 50 ppm (Fig. 13 and Table 65). In the presence of 600 ppm of $CaCO_3$, yields increased with increased P rates only through 25 ppm. Phosphorus applied in combination with lime rates of 1,200 ppm or higher had a significant negative effect on plant growth. It appears, therefore, that plant growth and the P rate which produced maximum yields decreased with increased lime rates. These results suggest that micronutrients in the Oxisol may have been deficient for the second Centrosema planting. Apparently, both lime and P aggravated this condition. However, the Oxisol was also P deficient and Centrosema responded to applied P on the unlimed soil. Lime decreases the availability of practically all micronutrients except Mo (43, 177, 313, 317, 361). Several authors (42, 70, 341) have also reported decreased Cu and Zn availabilities caused by high P rates. For the Spodosol, maximum Centrosema yields were attained at a lime rate of 600 ppm of $CaCO_3$ (Fig. 14) instead of 1,200 ppm as for the first planting (Fig. 11). Yields were consistently depressed by lime rates higher than 600 ppm. For the first planting, however, lime did not reduce yields with the exception of 1,800 ppm of $CaCO_3$ applied without P (Table 51).

Plant composition.--Phosphorus concentrations in Centrosema

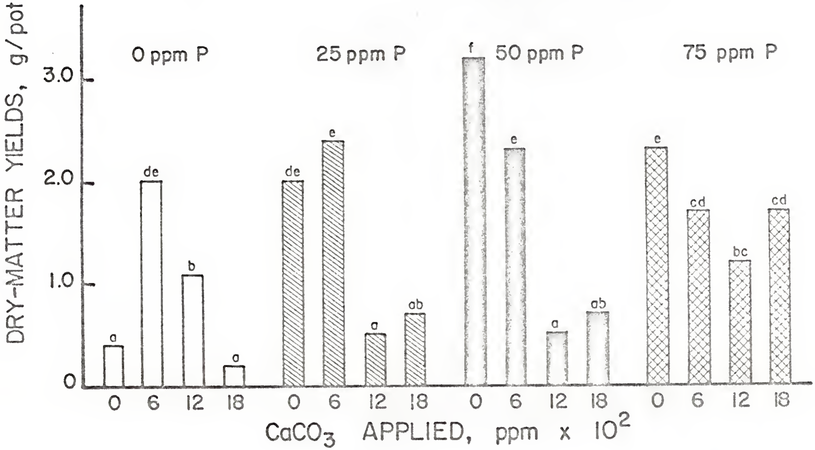

Fig. 13. Effects of lime and P applied to an Oxisol on Centrosema dry-matter yields from the second planting.

Bars not having a common letter are significantly different at the 5% level.

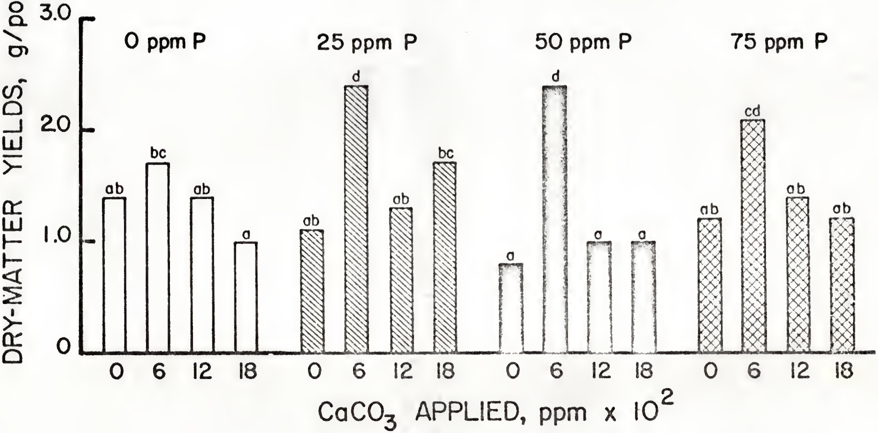

Fig. 14. Effects of lime and P applied to a Spodosol on Centrosema dry-matter yields from the second planting.

Bars not having a common letter are significantly different at the 5% level.

herbage varied from 0.15 to 0.31% for the Oxisol (Table 27) and from 0.18 to 0.56% for the Spodosol (Table 28). Plants from the Spodosol had much higher P concentrations than plants from the Oxisol. This was probably due to the higher P-fixation capacity of the Oxisol. For the Oxisol, applied P had little effect on herbage P concentrations (Table 27). For the Spodosol, however, the average P concentration increased from 0.23% in plants from the control to 0.48% when 75 ppm of P were applied (Table 28). Lime had little effect on P concentrations in plants from the Oxisol. For the Spodosol, the effect of lime on herbage P was not significant (Table 86). Phosphorus concentrations in plant tops from both soils were above the critical percentage of 0.16 reported for Centrosema (16).

For the Oxisol, K concentrations in plant tops were not significantly affected by lime (Table 27). Application of 25 ppm of P decreased the average K concentration in Centrosema herbage, compared with the control, from 1.71 to 1.50%. This effect, however, was confounded with a dilution effect due to increased yields. For the Spodosol, lime depressed herbage K concentrations (Table 28). The effect of applied P on K in plants from the unlimed Spodosol was small and confounded with differences in yields. Average K concentrations in plant tops were 1.53% for the Oxisol and 2.54% for the Spodosol. All K concentrations were higher than 0.75%, reported as critical for Centrosema (18).

For the Oxisol, average Ca concentrations in Centrosema herbage increased significantly from 2.00% for the control to 2.72% for the treatment with 1,800 ppm of $CaCO_3$ (Table 27). Phosphorus applied to the Oxisol had no significant effect on Ca concentrations. For the

Table 27. Effects of lime and P applied to an Oxisol on P, K, Ca, and Mg concentrations in oven-dry *Centrosema* herbage from the second planting.

CaCO3 applied	P applied, ppm				
	0	25	50	75	Mean
ppm	%				
	Herbage P				
0	0.15 a*	0.21 abcd	0.20 abcd	0.20 abcd	0.19
600	0.16 a	0.26 de	0.23 bcd	0.17 ab	0.20
1,200	0.19 abc	0.19 abc	0.31 e	0.16 a	0.24
1,800	0.18 ab	0.16 a	0.16 a	0.16 a	0.16
Mean	0.17	0.20	0.22	0.20	0.20
	Herbage K				
0	1.71	1.54	1.54	1.45	1.56 m
600	1.62	1.46	1.39	1.42	1.47 m
1,200	1.68	1.50	1.72	1.42	1.58 m
1,800	1.83	1.50	1.33	1.34	1.50 m
Mean	1.71 b	1.50 a	1.50 a	1.41 a	1.53
	Herbage Ca				
0	1.92	2.18	1.96	1.92	2.00 m
600	2.39	2.09	1.99	2.26	2.18 m
1,200	2.71	2.60	2.12	2.61	2.51 n
1,800	2.68	2.90	2.78	2.53	2.72 n
Mean	2.42 a	2.44 a	2.21 a	2.33 a	2.35
	Herbage Mg				
0	0.41	0.41	0.30	0.39	0.38 m
600	0.38	0.34	0.40	0.35	0.37 m
1,200	0.63	0.46	0.41	0.44	0.48 n
1,800	0.43	0.36	0.36	0.34	0.37 m
Mean	0.46 b	0.39 ab	0.37 a	0.38 a	0.40

* Numbers within element groups not followed by a common letter, within letter groups a-e and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 85.

Table 28. Effects of lime and P applied to a Spodosol on P, K, Ca, and Mg concentrations in oven-dry Centrosema herbage from the second planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	%				
	Herbage P				
0	0.18	0.31	0.55	0.56	0.40 m
600	0.26	0.28	0.50	0.49	0.38 m
1,200	0.30	0.40	0.45	0.44	0.40 m
1,800	0.19	0.24	0.34	0.43	0.30 m
Mean	0.23 a*	0.31 a	0.46 b	0.48 b	0.37
	Herbage K				
0	2.91 d	2.76 cd	3.54 e	2.73 cd	2.98
600	2.52 bcd	2.49 bc	2.28 ab	2.42 abc	2.43
1,200	2.44 bc	2.20 ab	2.73 cd	2.72 cd	2.52
1,800	2.25 ab	2.02 a	2.31 ab	2.39 abc	2.24
Mean	2.53	2.37	2.72	2.56	2.54
	Herbage Ca				
0	0.58 a	0.99 cd	0.67 ab	0.92 bcd	0.79
600	0.81 abc	1.11 cde	1.18 def	1.15 cdef	1.06
1,200	1.49 fg	1.41 efg	1.61 gh	1.56 gh	1.52
1,800	2.08 i	1.49 fg	1.89 hi	1.74 ghi	1.80
Mean	1.24	1.25	1.34	1.34	1.29
	Herbage Mg				
0	0.33	0.45	0.35	0.38	0.38 n
600	0.21	0.28	0.27	0.20	0.24 m
1,200	0.18	0.19	0.20	0.23	0.20 m
1,800	0.24	0.18	0.21	0.19	0.20 m
Mean	0.24 a	0.28 a	0.26 a	0.25 a	0.26

* Numbers within element groups not followed by a common letter, within letter groups a-i and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 86.

Spodosol, lime increased the average herbage Ca concentration from 0.79% for unlimed soil to 1.80% for soil limed with 1,800 ppm of $CaCO_3$ (Table 28). Applied P increased Ca concentrations in plant tops from the Spodosol limed with 600 ppm of $CaCO_3$. Phosphorus, however, had no significant effect on Ca concentrations in plants from the Spodosol limed with 1,200 or 1,800 ppm. For the Oxisol, Ca concentrations in Centrosema were higher than the critical percentage of 1.35 (15). For the Spodosol, Ca was generally below the critical percentage at low lime rates, 0 and 600 ppm of $CaCO_3$, but it appeared to be adequate at higher lime rates.

For the Oxisol, average Mg concentrations in plant tops were slightly decreased by application of 1,200 ppm of $CaCO_3$, compared with the other lime rates (Table 27). Average Mg concentrations decreased with increased P rates through 50 ppm; this effect, however, was confounded with dilution effects due to increased yields. The average Mg concentration in plants from the Oxisol was 0.40%. For the Spodosol, application of 600 ppm of $CaCO_3$ decreased Mg in Centrosema herbage, compared with the unlimed treatment, from 0.38 to 0.24%; higher lime rates had no further effect on Mg concentrations (Table 28). Applied P had no significant effect on Mg in plants from the Spodosol. Magnesium in Centrosema from this soil ranged from 0.18 to 0.45%; these concentrations are similar to values of 0.10 to 0.35% Mg reported by Embleton (114) for numerous plants showing Mg deficiency symptoms. Magnesium concentrations in plants from the Oxisol did not appear to be deficient.

Manganese concentrations in plant tops ranged from 59 to 180 ppm for the Oxisol (Table 29) and from 46 to 328 ppm for the Spodosol

Table 29. Effects of lime and P applied to an Oxisol on Mn, Cu, Zn, and Fe concentrations in oven-dry *Centrosema* herbage from the second planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	ppm				
			Herbage Mn		
0	158	180	125	131	148 o
600	100	117	90	113	105 n
1,200	65	66	64	69	66 m
1,800	64	67	59	76	66 m
Mean	97 ab*	108 b	84 a	97 ab	96
			Herbage Cu		
0	14	9	11	10	11 m
600	14	14	9	8	11 m
1,200	53	14	45	11	31 n
1,800	10	12	13	26	15 m
Mean	23 a	12 a	20 a	14 a	17
			Herbage Zn		
0	268 c	39 a	45 ab	49 ab	100
600	49 ab	47 ab	39 a	41 a	44
1,200	75 b	54 ab	49 ab	49 ab	57
1,800	46 ab	46 ab	49 ab	42 a	46
Mean	110	46	46	42	61
			Herbage Fe		
0	382	296	354	248	320 m
600	254	286	400	260	300 m
1,200	300	313	505	310	357 m
1,800	308	225	231	444	302 m
Mean	311 a	280 a	372 a	316 a	320

* Numbers within element groups not followed by a common letter, within groups a-c and m-o, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 87.

(Table 30). Applied P had little effect on Mn concentrations in Centrosema herbage from either soil. Manganese in the plant decreased with increased lime rates through 1,200 ppm of $CaCO_3$. Copper concentrations in plant tops varied from 8 to 53 ppm for the Oxisol (Table 29) and from 8 to 17 ppm for the Spodosol (Table 30). All Cu concentrations were higher than 4 ppm, the concentration cited as critical for several tropical legumes by Andrew and Thorne (20). Lime and applied P markedly reduced Zn concentrations in Centrosema herbage from the Oxisol (Table 29). Applications of 600 ppm of $CaCO_3$ and 25 ppm of P reduced Zn concentrations in plant tops, compared with the control, from 268 ppm to 47 ppm. Further applications of lime or P had no significant effect on Zn in plants. For the Spodosol, application of 600 ppm of $CaCO_3$ significantly reduced average Zn concentrations in plant tops; higher lime rates, however, had no significant effect on herbage Zn (Table 30). Zinc concentrations in plants from both soils were higher than deficiency levels, 20 to 25 ppm, reported by Chapman (76) for numerous plants. Iron levels in Centrosema herbage ranged from 225 to 505 ppm for the Oxisol (Table 30). Experimental variability was large for this determination and consequently neither lime nor P appeared to have any significant effect on Fe concentrations.

Nature of the lime X P interaction

Results from liming experiment 1 suggested that lime-induced yield depressions were related to reduced P availability in the Oxisol. For example, it can be seen in Fig. 9 that in the presence of 50 ppm of applied P, Centrosema dry-matter yields decreased from 12.0 g/pot for the 600 ppm lime treatment to 4.3 g/pot for the 1,200

Table 30. Effects of lime and P applied to a Spodosol on Mn, Cu, Zn, and Fe concentrations in oven-dry *Centrosema* herbage from the second planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	ppm				
			Herbage Mn		
0	291 ef*	248 de	328 f	247 de	278
600	183 c	119 b	190 c	214 cd	176
1,200	95 ab	84 ab	120 b	94 ab	98
1,800	49 a	46 a	55 a	60 a	52
Mean	154	124	173	154	151
			Herbage Cu		
0	8	10	11	12	10 m
600	12	11	12	10	11 mn
1,200	17	15	14	13	15 o
1,800	17	12	11	17	14 no
Mean	14 a	12 a	12 a	13 a	13
			Herbage Zn		
0	104	91	110	96	100 n
600	76	66	64	61	67 m
1,200	69	57	61	57	61 m
1,800	68	47	57	68	60 m
Mean	79 b	65 a	73 ab	70 ab	72
			Herbage Fe		
0	139	263	136	120	164 m
600	179	142	151	123	149 m
1,200	108	118	173	127	132 m
1,800	168	137	152	178	159 m
Mean	148 a	165 a	153 a	137 a	151

* Any numbers within element groups not followed by a common letter, within letter groups a-f and m-o, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 88.

ppm lime treatment. However, in the presence of 75 ppm of applied P, a similar increase in lime rates decreased yields, for the same legume, only from 13.5 to 8.0 g/pot. In other words, 75 ppm of applied P reduced the magnitude of the lime-induced yield depression.

Some investigators have reported a decrease in P availability with liming (30, 212, 271, 284, 338). Kamprath[1] indicated that one possible factor determining the effect of lime on P availability could be the strength of P adsorption by some soils. This author explained that when P is strongly bound, a high concentration of Ca can reduce P availability through formation of Ca phosphates. Although the statement by Kamprath is general in nature, available evidence (1, 108, 129, 183, 215, 226, 262) appears to support his contention that lime may decrease P availability through its effect on the bonding strength of P adsorbed on soil materials. Evidence in the literature (108, 129, 179, 226), however, seems to indicate that P applied to limed soils results in increased content of Al phosphate in the soil rather than Ca phosphate. It is possible that the method used for the determination of soil P fractions is not adequate for the separation of freshly precipitated phosphates. The original Chang and Jackson procedure (73) was largely developed for virgin and unfertilized soils. When this method is applied to soils recently limed and fertilized with P, the phosphates extracted may be of uncertain nature. Most of the controversy concerning this method has dealt with the NH_4F reagent. It has been reported (124, 125), for example, that P extracted by the NH_4F solution may be re-adsorbed on the surface of Fe oxide particles in the soil. It is also possible, however, that the solubilities of recently precipitated Ca phosphates in NH_4Cl, NH_4F, and NaOH solutions are greater than that expected from Chang and Jackson's initial work. Another explanation to account for the increase in Al phosphate is that liming an acid soil may actually favor the adsorption of P on Al phosphate or hydroxy-Al surfaces. A large proportion of the phosphate in Chang and Jackson's Al fraction has been reported to be exchangeable with P32 (108), which suggests that this fraction includes a significant proportion of adsorbed P (262). One possible mechanism for the adsorption of P by Al compounds can be postulated using ideas recently expounded by Hsu and Bates (183). These authors postulated the formation of positively charged hydroxy-Al polymers when Al is neutralized with a base. According to them, Al ions on the polymer surface are not completely neutralized until pH reaches a value of approximately 8; therefore, Al can react with phosphate or other similar anion. Liming may increase the rate of Al polymerization through its effect on soil pH; increased Al polymerization could result in new reactive sites for phosphate adsorption. Hsu (182) indicated that hydrolysis, polymerization, and reaction of Fe with phosphates may follow a similar mechanism to that of Al. Calcium ion can also increase phosphate adsorption as reported by Barrow (31) who found that at a given concentration of phosphate, adsorption of phosphate increased markedly with increased Ca concentrations in the equilibrating solution; Ca concentrations ranged from 0 to 0.02M as $CaCl_2$, and P concentrations in the supernatant solution varied from 0 to 0.6 ppm.

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[1] Kamprath, E. J., 1971. Potential detrimental effects from liming highly weathered soils to neutrality. Soil Crop Sci. Soc. Florida, Proc. 31. In press.

Experiment 2

This experiment was conducted to study plant response to lime with various combinations of essential nutrients. Nutrients applied and rates are listed in Table 6. The soils used were an Oxisol from Guatemala and an Entisol from Costa Rica. The soils were planted to P. lathyroides and replanted to Siratro. Lime rates used were identical to those in experiment 1 (0, 600, 1,200, and 1,800 ppm of $CaCO_3$). Three nutrient combinations were applied to the Oxisol, i.e., control, all nutrients added, and all nutrients added except Fe. Only the first two combinations were applied to the Entisol. Iron was omitted to investigate the possibility of lime-induced Fe deficiency. These nutrient combinations were added each with two rates of P, 0 and 50 ppm.

Plant growth.--Phaseolus lathyroides and Siratro dry-matter yields (Tables 31 and 89) were extremely low when P was not applied and plant response to lime lacked statistical significance for both soils. Therefore, this discussion will be restricted to treatments with applied P. When all nutrients except Fe were applied to the Oxisol, the response of P. lathyroides to lime (Fig. 15 and Table 89) was similar to that obtained with Centrosema in experiment 1, i.e., dry-matter yields increased with increased lime rates through 600 ppm of $CaCO_3$; thereafter, yields decreased with increased lime rates. Dry-matter yields of Siratro from the Oxisol (Fig. 15) increased with increased lime rates through 600 ppm; thereafter, 1,200 ppm of $CaCO_3$ had no effect and 1,800 ppm decreased yields.

For the Entisol (Table 31), lime had little effect on P. lathyroides yields. This lack of plant response was probably due to the poor growth

Table 31. Effects of lime, P, and nutrient combinations* applied to an Entisol on oven-dry P. lathyroides and Siratro herbage and root yields.

	P applied, ppm				
	0		50		
	Nutrient combinations*		Nutrient combinations		
$CaCO_3$ applied	None	All	None	All	Mean
ppm	g/pot				
	Phaseolus lathyroides herbage				
0	0.3 a**	0.4 ab	1.4 f	1.0 cde	0.8
600	0.7 bc	0.4 ab	1.2 ef	1.1 def	0.9
1,200	0.3 a	0.3 a	0.8 cd	1.1 def	0.6
1,800	0.4 ab	0.4 ab	0.7 bc	1.0 cde	0.6
Mean	0.4	0.4	1.0	1.1	0.7
	Phaseolus lathyroides roots				
0	0.3 a	0.3 a	1.2 d	1.3 d	0.8
600	0.5 ab	0.4 ab	1.1 d	1.1 d	0.8
1,200	0.4 ab	0.3 a	0.7 bc	1.0 cd	0.6
1,800	0.3 a	0.3 a	0.6 ab	0.7 bc	0.5
Mean	0.4	0.3	0.9	1.0	0.7
	Siratro herbage				
0	1.5 abc	1.2 abc	3.6 gh	1.6 abc	2.0
600	1.0 ab	0.9 a	3.1 fg	2.6 def	1.9
1,200	0.8 a	1.0 ab	2.8 efg	1.8 bcd	1.6
1,800	0.9 a	1.1 ab	2.0 cde	1.3 abc	1.3
Mean	1.0	1.0	2.9	1.8	2.0

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within herbage and root groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 103.

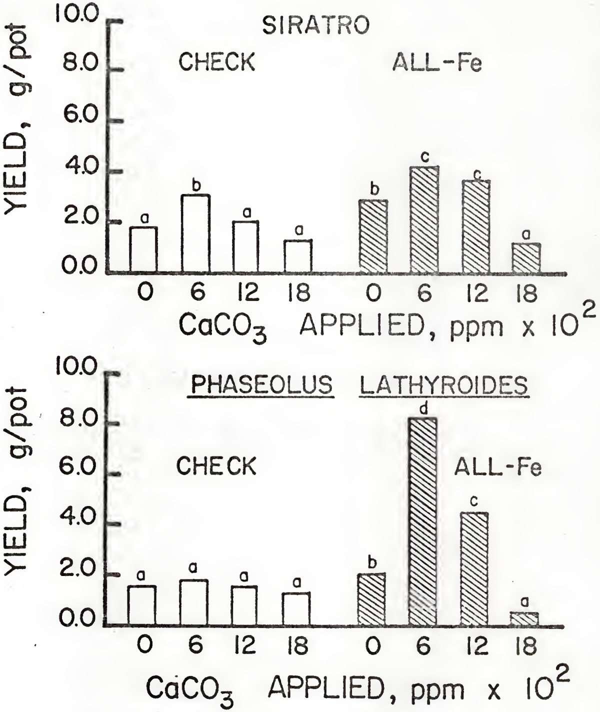

Fig. 15. Effects of lime with and without other applied nutrients on oven-dry P. lathyroides and Siratro herbage yields from an Oxisol.

Bars within legume groups not having a common letter are significantly different at the 5% level.
]

of this legume at all lime rates. Siratro grew better than P. lathyroides on this soil. Siratro herbage yields were reduced by application of 1,800 ppm of $CaCO_3$ when nutrients were not applied. In the presence of applied nutrients, yields increased with increased lime rates through 600 ppm of $CaCO_3$; thereafter, lime reduced yields.

Phaseolus lathyroides and Siratro yields increased significantly when Fe was not applied to the Oxisol (Table 89). For the Entisol, Fe was not omitted from the nutrient combination; this may account for the poor growth of both legumes, particularly P. lathyroides.

For the Oxisol, applied nutrients increased the response of both legumes to lime (Fig. 15). However, the response trend was similar to that obtained without applied nutrients.

Plant composition.--Phosphorus concentrations in P. lathyroides herbage and roots from the Oxisol (Tables 32 and 94) and Entisol (Tables 34 and 95) were all under 0.20%, the critical concentration reported for this legume (16). Phosphorus concentrations in Siratro herbage ranged from 0.10 to 0.21% for the Oxisol (Table 33) and from 0.06 to 0.15% for the Entisol (Table 35). Phosphorus concentrations in Siratro were higher than in P. lathyroides, but they were still below the critical concentration, 0.24% (16). Phosphorus concentrations were higher in plants from the Oxisol than from the Entisol, probably due to a higher P-fixation capacity for the latter. Apparently, plant growth was limited by a low P supply in both soils, particularly in the Entisol, even when 50 ppm of P were applied.

Siratro generally showed higher K concentrations (Tables 33 and 35) than P. lathyroides (Tables 32 and 34), particularly from the Entisol. For the Oxisol, herbage K concentrations ranged from 1.07 to 1.72% for P. lathyroides (Table 32) and from 1.05 to 2.42% for

Table 32. Effects of lime, P, and nutrient combinations* applied to an Oxisol on P, K, Ca, and Mg concentrations in oven-dry P. lathyroides herbage.

$CaCO_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	%						
				Herbage P			
0	0.04 ab**	0.04 ab	0.05 abc	0.13 gh	0.16 ij	0.14 hi	0.09
600	0.04 ab	0.04 ab	0.08 de	0.12 fgh	0.14 hi	0.18 j	0.10
1,200	0.04 ab	0.04 ab	0.07 cd	0.10 ef	0.16 ij	0.14 hi	0.09
1,800	0.06 bcd	0.03 a	0.08 de	0.11 fg	0.11 fg	0.10 ef	0.08
Mean	0.04	0.04	0.07	0.12	0.14	0.14	0.09
				Herbage K			
0	1.51 fg	1.67 hi	1.72 i	1.64 hi	1.66 hi	1.55 gh	1.63
600	1.37 cde	1.47 efg	1.56 gh	1.45 efg	1.46 efg	1.49 efg	1.47
1,200	1.26 bc	1.39 def	1.40 def	1.30 cd	1.30 cd	1.40 def	1.34
1,800	1.17 a	1.42 def	1.25 bc	1.11 a	1.07 a	1.11 a	1.19
Mean	1.33	1.49	1.48	1.38	1.37	1.39	1.41

Table 32. Continued

CaCO$_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	%						
	Herbage Ca						
0	1.12 a	1.29 ab	1.78 d	1.32 ab	1.42 bc	1.76 d	1.45
600	1.60 cd	1.75 d	2.50 ghij	2.05 e	2.17 ef	2.25 ef	2.05
1,200	2.33 fg	2.58 hijk	2.62 ijk	2.17 ef	2.38 fgh	2.29 fg	2.40
1,800	2.29 fg	2.31 fg	2.63 jk	2.40 fghi	2.74 k	2.75 k	2.52
Mean	1.83	1.98	2.38	1.98	2.18	2.26	2.11
	Herbage Mg						
0	0.44 a	0.49 ab	0.62 g	0.56 cdef	0.58 efg	0.58 efg	0.55
600	0.58 efg	0.49 ab	0.54 bcde	0.57 defg	0.62 g	0.60 fg	0.57
1,200	0.52 bcd	0.52 bcd	0.49 ab	0.53 bcde	0.60 fg	0.49 ab	0.53
1,800	0.58 efg	0.57 defg	0.55 cdef	0.51 bc	0.51 bc	0.55 cdef	0.55
Mean	0.53	0.52	0.55	0.54	0.58	0.56	0.55

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 99.

Table 33. Effects of lime, P, and nutrient combinations* applied to an Oxisol on P, K, Ca, and Mg concentrations in oven-dry Siratro herbage.

	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
CaCO3 applied	None	All	All-Fe	None	All	All-Fe	Mean
ppm	%						
				Herbage P			
0	0.10 abc **	0.14 de	0.13 cd	0.17 ef	0.14 de	0.20 fg	0.15
600	0.21 g	0.13 cd	0.11 bcd	0.20 fg	0.14 de	0.11 bcd	0.15
1,200	0.12 bcd	0.14 de	0.13 cd	0.12 bcd	0.20 fg	0.10 bc	0.14
1,800	0.11 bcd	0.13 cd	0.14 de	0.09 ab	0.12 bcd	0.06 a	0.11
Mean	0.14	0.14	0.13	0.15	0.15	0.12	0.14
				Herbage K			
0	1.05 a	1.23 abc	1.21 ab	1.71 gh	1.56 defg	2.42 k	1.53
600	1.52 cdefg	1.30 abcde	2.23 jk	1.74 ghi	2.24 jk	1.81 ghi	1.81
1,200	1.69 fg	1.39 bcdef	2.14 jk	1.82 ghi	2.28 jk	1.68 fg	1.83
1,800	1.27 abcd	1.35 abcde	2.05 ij	1.66 fg	2.00 hij	1.60 efg	1.66
Mean	1.38	1.32	1.91	1.73	2.02	1.88	1.71

Table 33. Continued

CaCO$_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	%						
	Herbage Ca						
0	2.41 efg	2.28 cde	2.18 cd	2.09 c	2.10 cd	1.63 a	2.12
600	2.47 efg	2.78 hi	2.23 cd	2.43 efg	2.30 cde	1.75 ab	2.33
1,200	3.26 kl	2.40 efg	2.40 efg	2.50 efg	2.31 def	1.88 b	2.56
1,800	3.08 jkl	3.47 l	2.56 gh	2.54 fg	2.58 gh	2.60 gh	2.81
Mean	2.81	2.88	2.34	2.39	2.32	1.97	2.45
	Herbage Mg						
0	1.30 efg	1.31 fg	1.23 ef	0.98 d	0.90 bcd	0.80 abc	1.09
600	1.46 hi	1.50 i	0.93 cd	0.97 d	0.91 bcd	0.72 a	1.08
1,200	1.38 ghi	1.35 fgh	0.80 abc	0.86 abcd	0.80 abc	0.73 a	0.99
1,800	1.16 e	1.22 ef	0.78 ab	0.79 ab	0.82 abc	0.84 abcd	0.94
Mean	1.33	1.35	0.94	0.90	0.86	0.77	1.03

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 108.

Table 34. Effects of lime, P, and nutrient combinations* applied to an Entisol on P, K, Ca, and Mg concentrations in oven-dry P. lathyroides herbage.

	P applied, ppm				
	0		50		
CaCO$_3$	Nutrient combinations*		Nutrient combinations		
applied	None	All	None	All	Mean
ppm	---------------	---------------	%	---------------	---------------
			Herbage P		
0	0.04 ab**	0.04 ab	0.07 cd	0.10 e	0.06
600	0.05 bc	0.04 ab	0.08 de	0.09 de	0.07
1,200	0.03 ab	0.03 ab	0.10 e	0.10 e	0.07
1,800	0.03 ab	0.02 a	0.09 de	0.10 e	0.06
Mean	0.04	0.03	0.09	0.10	0.07
			Herbage K		
0	0.86 a	1.05 abcd	1.18 bcd	1.31 d	1.10
600	1.01 abc	1.09 abcd	1.23 cd	1.32 d	1.16
1,200	0.94 ab	1.06 abcd	1.25 d	1.29 d	1.14
1,800	0.96 abc	1.20 bcd	1.22 cd	1.33 d	1.18
Mean	0.94	1.10	1.22	1.31	1.15
			Herbage Ca		
0	2.99 c	2.85 bc	2.71 b	2.52 a	2.77
600	3.31 d	2.99 c	2.82 b	2.75 b	2.97
1,200	3.23 d	3.27 d	2.99 c	3.60 e	3.27
1,800	3.63 e	3.58 e	3.24 d	3.60 e	3.51
Mean	3.29	3.17	2.94	3.12	3.13
			Herbage Mg		
0	0.99 h	0.86 g	0.61 bc	0.56 ab	0.76
600	0.81 fg	0.70 de	0.53 a	0.54 ab	0.65
1,200	0.66 cd	0.64 cd	0.51 a	0.50 a	0.58
1,800	0.80 fg	0.74 ef	0.50 a	0.50 a	0.64
Mean	0.82	0.74	0.54	0.53	0.66

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 104.

Table 35. Effects of lime, P, and nutrient combinations* applied to an Entisol on P, K, Ca, and Mg concentrations in oven-dry Siratro herbage.

CaCO$_3$ applied	P applied, ppm				Mean
	0		50		
	Nutrient combinations*		Nutrient combinations		
	None	All	None	All	
ppm	%				
			Herbage P		
0	0.10 ab**	0.14 ab	0.15 b	0.11 ab	0.13
600	0.07 ab	0.07 ab	0.11 ab	0.11 ab	0.09
1,200	0.06 a	0.06 a	0.11 ab	0.10 ab	0.08
1,800	0.06 a	0.09 ab	0.10 ab	0.11 ab	0.09
Mean	0.07	0.09	0.12	0.11	0.10
			Herbage K		
0	1.67 abc	1.63 abc	1.58 ab	1.67 abc	1.64
600	1.68 abc	1.53 a	1.92 c	1.82 abc	1.74
1,200	1.57 ab	1.66 abc	1.85 bc	1.92 c	1.75
1,800	1.70 abc	1.88 c	1.88 c	1.87 c	1.83
Mean	1.66	1.68	1.81	1.82	1.74
			Herbage Ca		
0	1.73 a	1.90 abc	1.81 ab	2.00 bc	1.86
600	2.29 de	2.53 fg	1.88 abc	2.24 d	2.24
1,200	2.47 efg	2.63 g	2.09 cd	2.31 de	2.38
1,800	2.50 efg	2.55 fg	2.24 d	2.37 ef	2.42
Mean	2.25	2.40	2.01	2.23	2.22
			Herbage Mg		
0	1.00 bc	1.09 c	0.85 a	0.95 ab	0.97
600	0.89 ab	1.01 bc	0.97 abc	1.00 bc	0.97
1,200	0.92 ab	1.00 bc	0.96 abc	0.91 ab	0.95
1,800	0.91 ab	0.98 abc	1.00 bc	0.96 abc	0.96
Mean	0.93	1.02	0.95	0.96	0.97

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 110.

Siratro (Table 33). For the Entisol, herbage K ranged from 0.86 to 1.33% for P. lathyroides (Table 34) and from 1.53 to 1.92% for Siratro (Table 35). Average K in P. lathyroides herbage from the Oxisol decreased from 1.63% for the unlimed treatment to 1.19 when 1,800 ppm of $CaCO_3$ were applied (Table 32). In contrast, average K concentrations in Siratro from the Entisol increased from 1.64% for the unlimed treatment to 1.83% for the 1,800 ppm lime treatment (Table 35). Lime had little effect on average K concentrations in Siratro from the Oxisol (Table 33) and P. lathyroides from the Entisol (Table 34). All K concentrations were above the critical percentage of 0.75 as reported by Andrew and Robins (18) for both legumes.

Lime at a rate of 1,800 ppm of $CaCO_3$, compared with the unlimed treatment, increased average Ca concentrations in P. lathyroides herbage from 1.45 to 2.52% for the Oxisol (Table 32) and from 2.77 to 3.51% for the Entisol (Table 34). Average Ca concentrations in Siratro were increased by 1,800 ppm of $CaCO_3$, compared with the unlimed treatment, from 2.12 to 2.81% for the Oxisol (Table 33) and from 1.86 to 2.42% for the Entisol (Table 35). For the Oxisol, Siratro generally contained more Ca than P. lathyroides, particularly without applied P. In contrast, Ca in P. lathyroides was higher when grown on the Entisol. For the Oxisol, the average herbage Mg was 0.55% for P. lathyroides (Table 32) and 1.03% for Siratro (Table 33). For the Entisol, average Mg concentrations for the same legumes were 0.66 and 0.97%, respectively (Tables 34 and 35).

The effects of lime on concentrations of Mn, Cu, Zn, and Fe in the herbage of P. lathyroides and Siratro are shown in Tables 90 through 93. In general, these effects were similar to those from liming experiment 1. Manganese and Zn concentrations decreased with increased lime rates; however, Cu and Fe did not vary significantly with lime. For the Oxisol, Mn in Siratro was generally higher than in _P. lathyroides_; for the Entisol, however, Mn in _P. lathyroides_ was higher. Copper and Fe concentrations in both legumes were similar for both soils.

Manganese, Cu, Zn, and Fe in _P. lathyroides_ and Siratro herbage from both soils were above critical concentrations, i.e., 10 to 25 ppm for Mn (209), 5 ppm for Cu (20), 20 to 25 ppm for Zn (76), and 10 to 70 ppm for Fe (376). Chemical composition of oven-dry _P. lathyroides_ roots is shown in Tables 95 through 97.

Exchangeable Ca and soluble salts.--Exchangeable Ca and soluble salts were determined in the Oxisol and Entisol at different lime rates; the Spodosol was also included for comparison. Exchangeable Ca in 10-g soil samples was extracted with 100 ml of 1N KCl. Soluble salts were determined by measuring the electrical conductivities of saturated soil extracts.

Exchangeable Ca (Table 112) increased with application of 1,800 ppm of $CaCO_3$, compared with the unlimed soil, from 3.25 to 5.80 meq/100 g for the Oxisol, from 0.99 to 1.97 meq/100 g for the Spodosol, and from 6.30 to 7.48 meq/100 g for the Entisol. Calcium saturation in the Entisol was only slightly affected by liming due to the high CEC of this soil. However, Ca saturations were markedly increased for the Oxisol and Spodosol.

Data in Table 113 show electrical conductivities of saturated extracts from the Oxisol and Entisol. According to the electrical conductivity standards used by the United States Salinity Laboratory, salinity is not likely to affect plant growth when conductivities of saturated extracts are less than 2 mmhos/cm; yields of very sensitive crops may be restricted from 2 to 4 mmhos/cm; yields of many crops will be restricted from 4 to 8 mmhos/cm; and only tolerant plants will grow satisfactorily from 8 to 16 mmhos/cm (305). For the Oxisol, conductivities were less than 2 mmhos/cm and consequently salinity effects on plant growth would be negligible. For the Entisol, however, conductivities ranged from 4.8 to 6.4 mmhos/cm, suggesting adverse effects of salts on plant growth, particularly of the more sensitive plant species.

Phosphorus Experiments

Experiment 1

Five-gram soil samples were treated with 2-ml solutions of NaH_2PO_4 to give final concentrations of P in the soil of 0, 50, 100, 150, 200, 300, and 500 ppm as described by Waugh and Fitts (377). The samples were incubated at room temperature, approximately 25C, for 72 hours and extracted with Bray-P2 reagent, 0.03N NH_4F and 0.1N HCl. The results for the four soils are presented in Fig. 16 and Table 114.

The amounts of P extracted from the four soils increased linearly with increased P rates. Coefficients of linear correlation for the four soils were highly significant, indicating that the relationships between P extracted and P added for these soils could be best described by straight lines. Linear regression equations are presented in Fig. 16. The amounts of P extracted from untreated soils were 7.4 ppm for the Inceptisol, 11.9 ppm for the Oxisol, 21.1 ppm for the Spodosol, and 59.6 ppm for the Entisol. With the exception of the Entisol,

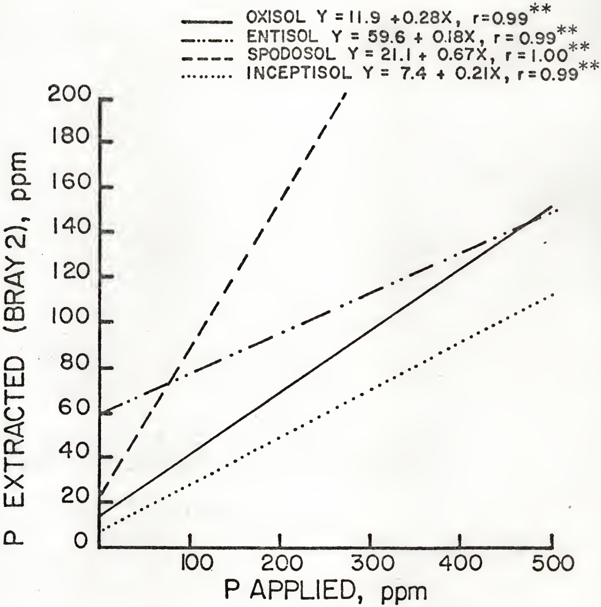

Fig. 16. Phosphorus extracted by Bray-P2 reagent from four soils after 72-hour incubation with different rates of applied P.

these values appear to be low compared with values cited in the literature (154, 236, 237, 377). The slope for each regression equation determines the increase in extracted P associated with a unit increase in applied P. The value of the slope is, therefore, inversely proportional to the P-retention capacity of the soil. Slopes were 0.18 for the Entisol, 0.21 for the Inceptisol, 0.28 for the Oxisol, and 0.67 for the Spodosol. The Entisol showed the highest P-retention capacity of all soils although extractable-P values from the untreated soil were relatively high. The Spodosol showed the lowest P-retention capacity. The linear relationship obtained between applied and extracted P indicated that a constant proportion of the applied P was retained by the soil against Bray-reagent extraction. One would expect, therefore, to obtain plant growth responses to applied P even at low rates of application. Data in Table 114 show that liming the Oxisol with 1,800 ppm of $CaCO_3$ did not significantly affect the amount of P extracted; the only exception occurred at the highest P rate, 500 ppm, where liming significantly decreased the amount of P extracted from 159 ppm for the unlimed soil to 134 ppm when 1,800 ppm of $CaCO_3$ were applied.

Experiment 2

Originally, the amount of P to be applied in this greenhouse experiment was to be calculated from information obtained in the previous experiment. The idea was to select the rate of applied P that would produce a sudden increase in extractable P; theoretically, this rate would more than overcome the effect of P fixation and supply the soil with plant-available P. The rate determined by this method would be designated as X value. However, since there was no sudden increase in extractable P at any rate within the P range studied, 100 ppm was selected as an approximation for the X value for all soils; this approach followed suggestions made by Waugh and Fitts (377). Phosphorus applications were made to the Inceptisol, Oxisol, and Entisol at rates of 0, 50, 100, and 200 ppm of P. The source of P was NaH_2PO_4. Phaseolus lathyroides herbage and roots were harvested approximately 3 months after planting. The Oxisol and Inceptisol were subsequently planted to Siratro; tops and roots of Siratro were harvested 14 weeks after planting. A basal fertilization was applied including all essential plant nutrients except N, P, and Fe.

Plant growth.--The three soils responded markedly to applied P (Fig. 17). However, the only soil that reached a point of relative P sufficiency was the Inceptisol. Optimum yields from this soil were obtained at a rate of 100 ppm of P. It can be seen in Fig. 16 that 100 ppm of applied P increased extractable P, compared with the untreated soil, from 7 to 28 ppm; the latter concentration would be considered low, based on the scarce information available in the literature (154, 236, 237, 377); however, it was evidently sufficient for optimum legume growth for this soil under the experimental conditions of this study.

For the Oxisol and Entisol, dry-matter yields increased linearly with increased rates of applied P; however, a yield plateau was never attained. Evidently, optimum P rates for these two soils were higher than 200 ppm. Phosphorus in P. lathyroides herbage at maximum growth was 0.18% for the Oxisol and 0.32% for the Entisol (Fig. 17). In contrast, P in P. lathyroides at optimum growth was 0.18% for the Inceptisol. According to Andrew and Robins (16), the critical P

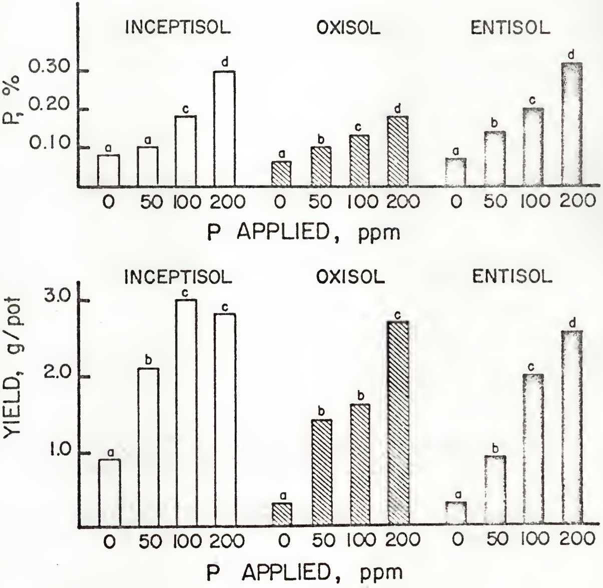

Fig. 17. Effects of P applied to three tropical soils on oven-dry yields and P concentrations in *P. lathyroides* herbage.

Bars within soil groups not having a common letter are significantly different at the 5% level.

concentration for P. lathyroides is 0.20%. This inconsistent relationship between herbage P concentrations and optimum P rates supports the contention that critical nutrient concentrations must be interpreted with caution. Variable soil factors and nutrient interactions, particularly those exerting their influence within the plant at the sites of nutrient translocation or utilization, may play an important role in determining the optimum nutrient concentration for a given plant tissue at a specified age.

Applications of 200 ppm of P to the Oxisol and Entisol produced extractable P levels of 60 ppm for the Oxisol and 96 ppm for the Entisol (Fig. 16). Plant-available P in these soils, however, were not sufficient for optimum growth under greenhouse conditions.

For the Inceptisol, Siratro response to applied P (Table 36) was similar to that of P. lathyroides. Optimum oven-dry Siratro herbage yields were obtained with 100 ppm of applied P. Phosphorus in Siratro herbage from the Inceptisol at optimum growth was 0.14% (Table 36); this concentration was markedly lower than 0.24% P, cited as critical for this legume by Andrew and Robins (16). Optimum growth of Siratro from the Oxisol was obtained with 100 ppm of applied P (Table 36). These results contradicted those obtained with P. lathyroides from the same soil (Fig. 17), but they can be explained as due to a larger P requirement by P. lathyroides as reported by other authors (16, 171). Phosphorus in Siratro herbage from the Oxisol at optimum growth was 0.14% (Table 36).

Plant composition.--Applied P had a marked synergistic effect on K uptake by P. lathyroides for all soils ($T_a$ble 37). For example, K increased from 1.60% in plants from the control to 3.73% when 100

Table 36. Effects of P applied to an Inceptisol and Oxisol on oven-dry yields and P, K, Ca, and Mg concentrations in Siratro herbage and roots under greenhouse conditions.

P applied	Yields	Nutrient concentrations			
		P	K	Ca	Mg
ppm	g/pot	%			
Inceptisol (herbage)					
0	0.4 a*	0.08 a	1.11 a	0.89 a	3.18 b
50	1.0 b	0.09 a	1.53 b	1.08 a	2.90 ab
100	2.0 c	0.14 b	1.89 c	0.97 a	2.74 ab
200	1.8 c	0.24 c	2.14 d	0.85 a	2.32 a
Inceptisol (roots)					
0	0.7 a	0.10 a	0.62 a	0.96 b	2.33 a
50	0.8 a	0.11 a	0.70 a	0.73 a	2.32 a
100	1.4 b	0.13 a	0.74 a	0.66 a	2.72 a
200	1.0 ab	0.21 b	0.93 b	0.70 a	2.23 a
Oxisol (herbage)					
0	0.1 a	0.08 a	0.81 a	1.54 a	1.02 a
50	0.3 a	0.09 a	0.88 a	1.57 a	1.04 a
100	1.0 b	0.14 b	1.95 b	1.96 ab	1.03 a
200	0.8 b	0.14 b	2.07 b	2.01 b	1.16 a
Oxisol (roots)					
0	0.5 a	0.11 a	0.28 a	1.75 c	0.43 a
50	0.5 a	0.10 a	0.42 a	1.46 b	0.53 a
100	0.6 a	0.14 b	0.81 b	1.60 bc	0.49 a
200	0.6 a	0.17 b	0.69 b	1.19 a	0.41 a

* Numbers within vertical columns, within soil-herbage or soil-root groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 124.

Table 37. Effects of P applied to an Inceptisol, Oxisol, and Entisol on oven-dry yields and P, K, Ca, and Mg concentrations in *P. lathyroides* herbage under greenhouse conditions.

P applied	Herbage yields	Nutrient concentrations			
		P	K	Ca	Mg
ppm	g/pot	%			
		Inceptisol			
0	0.9 a*	0.08 a	1.60 a	0.88 b	1.25 a
50	2.1 b	0.10 a	2.05 b	0.71 a	1.40 b
100	3.0 c	0.18 c	3.73 c	0.70 a	1.45 b
200	2.8 c	0.30 d	3.63 c	0.88 b	1.96 c
		Oxisol			
0	0.3 a	0.06 a	0.89 a	1.28 a	0.60 b
50	1.4 b	0.10 b	1.40 b	1.74 b	0.61 b
100	1.6 b	0.13 c	1.93 c	2.23 c	0.61 b
200	2.7 c	0.18 d	2.72 d	1.75 b	0.54 a
		Entisol			
0	0.3 a	0.07 a	1.38 a	2.73 a	0.66 a
50	0.9 b	0.14 b	2.63 b	2.71 a	0.66 a
100	2.0 c	0.20 c	3.58 c	2.71 a	0.75 a
200	2.6 d	0.32 d	3.79 c	2.57 a	0.66 a

* Numbers within vertical columns, within soil groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 120.

ppm of P were applied to the Inceptisol; thereafter, 200 ppm of P had no further effect on herbage K concentrations. For the Oxisol and Entisol, however, herbage K increased with increased P rates through 200 ppm. Increased K concentration in the plant was usually associated with increased plant growth. This fact lends support to the contention enunciated earlier that the effect of applied P on K uptake was probably due to a better developed root system in the presence of applied P. Phosphorus had similar effects on K concentrations in Siratro herbage from the Inceptisol and Oxisol (Table 36). Applied P increased Ca concentrations in P. lathyroides only for the Oxisol. Magnesium concentrations were increased by applied P only for the Inceptisol (Table 37).

For the Oxisol, 100 ppm of applied P, compared with the control, decreased herbage Mn from 765 to 138 ppm for P. lathyroides (Table 38) and from 1,199 to 164 ppm for Siratro (Table 39). These effects, however, were confounded with dilution effects due to increased yields. Copper in plant tops ranged from 3 to 13 ppm for both legumes (Tables 38 and 39). Copper concentrations were generally not affected by applied P. Herbage Zn (Tables 38 and 39) increased slightly with increased P rates for the Inceptisol and Oxisol; for the Entisol, however, Zn decreased with applied P, but this effect was confounded with growth effects. Iron in legume herbage from all soils was generally not affected by applied P.

The effect of applied P on the chemical composition of P. lathyroides roots (Tables 115 and 116) was generally similar to that for plant tops (Tables 37 and 38). However, Ca in roots decreased with increased P rates. Furthermore, applied P markedly decreased

Table 38. Effects of P applied to an Inceptisol, Oxisol, and Entisol on Mn, Cu, Zn, and Fe concentrations in oven-dry P. lathyroides herbage under greenhouse conditions.

P applied	Nutrient concentrations			
	Mn	Cu	Zn	Fe
ppm	ppm			
		Inceptisol		
0	64 a*	5 b	60 a	236 a
50	84 ab	4 ab	71 ab	190 a
100	96 b	3 a	72 ab	189 a
200	137 c	5 b	74 b	195 a
		Oxisol		
0	765 c	6 a	71 ab	331 b
50	328 b	8 b	65 a	270 ab
100	138 a	8 b	68 ab	237 a
200	140 a	8 b	77 b	227 a
		Entisol		
0	285 a	9 b	70 c	312 a
50	373 b	6 a	52 a	260 a
100	395 bc	7 a	58 b	280 a
200	423 c	10 b	50 a	320 a

* Numbers within vertical columns, within soil groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 121.

Table 39. Effects of P applied to an Inceptisol and Oxisol on Mn, Cu, Zn, and Fe concentrations in oven-dry Siratro herbage and roots under greenhouse conditions.

P applied	Nutrient concentrations			
	Mn	Cu	Zn	Fe
ppm	ppm			
		Inceptisol (herbage)		
0	126 a[*]	4 a	38 b	314 a
50	120 a	6 a	33 a	242 a
100	154 a	5 a	24 a	234 a
200	162 a	5 a	24 a	306 a
		Inceptisol (roots)		
0	303 a	18 a	57 a	4,624 a
50	400 a	22 a	91 a	4,676 a
100	647 b	20 a	63 a	3,146 a
200	632 b	19 a	56 a	3,288 a
		Oxisol (herbage)		
0	1,199 c	13 a	121 c	333 b
50	676 b	13 a	85 b	332 b
100	164 a	11 a	48 a	164 a
200	191 a	13 a	60 a	255 ab
		Oxisol (roots)		
0	1,372 d	37 a	127 b	5,219 a
50	1,020 c	30 a	121 ab	5,074 a
100	774 b	26 a	87 a	3,779 a
200	350 a	26 a	93 ab	2,741 a

[*] Numbers within vertical columns, within soil-herbage or soil-root groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 125.

Zn in roots from all soils; P had the opposite effect on herbage Zn from the Inceptisol and Oxisol (Table 38).

Experiment 3

Field experiments were established in Izabal, Guatemala, at the sites where Oxisol and Inceptisol samples were collected for greenhouse work. Phosphorus was applied as triple superphosphate (20.0% P) at rates of 0, 100, and 200 kg/ha of P. The Inceptisol was plowed to a depth of approximately 20 cm, harrowed and leveled. The Oxisol was hoed to a depth of about 8 cm. The fertilizer was broadcast and mixed with the top 8 cm of soil with a hoe. Molybdenum was applied to all plots at the rate of 1 kg/ha. The Inceptisol was planted to *Centrosema* and Siratro, and the Oxisol to *Centrosema*, Siratro, and *S. humilis*. All seeds were inoculated with the appropriate certified *Rhizobium* strain. Plant tops were harvested on March 27 to 29, 1969, 4 months after planting. Results are presented in Tables 40 through 43.

Plant growth.--Applied P through 200 kg/ha had no significant effects on oven-dry herbage yields of *Centrosema*, Siratro, and *S. humilis* (Tables 40 and 42). Similar results were obtained from a second harvest of *Centrosema* and Siratro from the Inceptisol (Table 117). These results are in sharp contrast to significant yield increases for *P. lathyroides* and Siratro obtained under greenhouse conditions. In the field, *Centrosema* and Siratro showed vigorous growth at all P rates. Furthermore, there was no visual evidence of nutrient deficiency symptoms. *Stylosanthes humilis* yields were affected by a poor plant stand due to low seed quality.

Application of 200 kg/ha of P, compared with the control, increased the amount of P extracted by Mehlich's reagent from the 0-8 cm

Table 40. Effects of P applied to an Inceptisol on oven-dry yields and N, P, K, Ca, and Mg concentrations in Centrosema and Siratro herbage from the first harvest at Izabal, Guatemala.

P applied	Herbage yields	Nutrient concentrations				
		N	P	K	Ca	Mg
ppm	kg/6 m^2	%				
		Centrosema				
0	4.1 a*	2.72 a	0.23 a	1.66 a	0.53 b	1.25 ab
100	4.8 a	2.76 ab	0.28 b	1.64 a	0.56 b	1.12 a
200	3.8 a	2.82 bc	0.29 b	1.49 a	0.54 b	1.74 abc
		Siratro				
0	4.9 a	2.79 bc	0.22 a	1.97 b	0.40 a	1.79 bc
100	5.0 a	2.80 bc	0.23 a	1.86 b	0.43 a	1.63 abc
200	4.7 a	2.85 c	0.27 b	1.85 b	0.45 a	1.90 c

* Numbers within vertical columns not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 126.

Table 41. Effects of P applied to an Inceptisol on Mn, Cu, Zn, and Fe concentrations in oven-dry Centrosema and Siratro herbage from the first harvest at Izabal, Guatemala.

P applied	Nutrient concentrations			
	Mn	Cu	Zn	Fe
ppm	ppm			
	Centrosema			
0	85 a*	16 a	56 c	3,325 a
100	82 a	13 a	40 ab	2,040 a
200	128 a	15 a	38 a	3,228 a
	Siratro			
0	93 a	14 a	50 bc	3,645 a
100	72 a	19 a	43 ab	3,073 a
200	113 a	14 a	38 a	3,365 a

* Numbers within vertical columns not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 127.

Table 42. Effects of P applied to an Oxisol on oven-dry yields and N, P, K, and Ca concentrations in Centrosema, Siratro, and S. humilis herbage from the first harvest at Izabal, Guatemala.

P applied	Herbage yields	Nutrient concentrations				
		N	P	K	Ca	Mg
ppm	kg/6 m^2	%				
		Centrosema				
0	5.2 b*	2.61 a	0.22 a	1.21 a	1.25 a	0.41 a
100	6.0 b	2.64 ab	0.26 ab	1.30 a	1.25 a	0.43 a
200	6.3 b	2.71 b	0.28 b	1.37 a	1.28 a	0.43 a
		Siratro				
0	11.2 c	2.87 c	0.24 ab	1.31 a	1.14 a	0.83 b
100	12.1 c	2.92 c	0.27 ab	1.45 a	1.00 a	0.75 b
200	13.3 c	2.96 cd	0.29 b	1.49 a	1.06 a	0.75 b
		S. humilis				
0	2.5 a	3.00 de	0.25 ab	1.25 a	1.78 b	0.51 a
100	3.4 a	3.04 e	0.29 b	1.35 a	1.74 b	0.48 a
200	2.2 a	3.14 f	0.29 b	1.17 a	1.74 b	0.56 a

* Numbers within vertical columns not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 128.

Table 43. Effects of P applied to an Oxisol on Mn, Cu, Zn, and Fe concentrations in oven-dry Centrosema, Siratro, and S. humilis herbage from the first harvest at Izabal, Guatemala.

P applied	Nutrient concentrations			
	Mn	Cu	Zn	Fe
ppm	ppm			
	Centrosema			
0	154 ab*	24 b	44 a	753 a
100	152 ab	22 b	44 a	665 a
200	171 abc	22 b	41 a	758 a
	Siratro			
0	126 a	15 a	40 a	460 a
100	128 a	15 a	36 a	965 a
200	128 a	14 a	35 a	970 a
	S. humilis			
0	230 cd	26 b	57 b	2,740 ab
100	256 d	24 b	58 b	4,123 b
200	209 cd	23 b	53 b	2,658 ab

* Numbers within vertical columns not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 129.

layer of soil from 4.3 to 28.7 ppm for the Oxisol and from 12.5 to 33.6 ppm for the Inceptisol (Table 119). Phosphorus extracted from the 8-12 cm layer of the Inceptisol increased from 2.4 ppm for the control to 7.3 ppm for the soil fertilized with 200 kg/ha of P.

Plant composition.--For the Inceptisol, 200 kg/ha of P, compared with the control, increased herbage P concentrations (Table 40) from 0.23 to 0.29% for *P. lathyroides* and from 0.22 to 0.27% for Siratro. Similar small increases in herbage P with increased P rates were obtained from the Oxisol (Table 42). Phosphorus in plants was generally higher than critical P concentrations, i.e., 0.16% for *Centrosema*, 0.24% for Siratro, and 0.17% for *S. humilis* (16). Phosphorus concentrations in plants from unfertilized field plots were as high as those in plants from the same soils fertilized with 200 ppm of P under greenhouse conditions (Tables 36 and 37). Evidently, legumes grown under field conditions were well supplied with P even from unfertilized plots.

Nitrogen concentrations in *Centrosema* herbage from both soils (Tables 40 and 42) increased slightly with increased P rates; N in *S. humilis* from the Oxisol also increased with applied P. Phosphorus fertilization had no significant effect on K concentrations. This result supports the contention stated earlier that the effects of applied P on K uptake and root development were closely associated.

Phosphorus applied to the Inceptisol and Oxisol had no significant effects on Ca, Mg, Mn, Cu, and Fe concentrations in the herbage of *Centrosema*, Siratro, and *S. humilis* (Tables 40 through 43). For the Inceptisol, application of 200 kg/ha of P, compared with the control, decreased herbage Zn concentrations from 56 to 38 ppm for *Centrosema* and from 50 to 38 ppm for Siratro; these effects were not significant for the Oxisol. Copper concentrations in legume herbage from the field experiments were higher than those in plants from the greenhouse. On the other hand, Mn in plant tops, particularly from the Oxisol, was markedly lower in legumes grown in the field.

Concentrations of all nutrients in field-grown legumes were above critical values reported in the literature (15, 18, 20, 76, 114, 209, 376). The only exception was Ca in Centrosema and Siratro herbage from the Inceptisol (Table 40); these values were markedly lower than 1.35%, the critical Ca concentration calculated from data by Andrew and Norris (15).

Lack of Agreement Between Greenhouse and Field Results

Plant response to applied P in the field was markedly different from that obtained in the greenhouse. It appeared that some plant environmental factor affected the delivery of P from soil to plant. Many soil and meterological conditions are changed when soils are brought into the greenhouse. Soils are dried, sieved, stored, and often sterilized before being used in the greenhouse. Wetting and drying can have pronounced effects on the availability of some nutrients in the soil; for example, increased fixation of K^+ and NH_4^+ in soils with expanding 2:1 lattice clays has been reported (43, 313). Yuan, Robertson, and Neller (390) reported that wetting and drying some Florida soils significantly decreased the percentage of Al phosphate and increased that of Fe phosphate. In this investigation, plant-available Mn in the Oxisol was greater in the greenhouse than in the field. Sterilization can also affect soil microbiological processes such as organic matter mineralization and mycorrhiza development. Soil moisture and structure are also altered in pot culture. Soil and open-air temperatures are considerably higher in the greenhouse than in the field, especially during the summer. Solar radiation in the greenhouse may be one-half to one-third that in the field. Volume of soil per plant is one factor that has been reported to have a marked influence on plant growth and P uptake. For example, Baker and Woodruff (25) found that corn grown in pot culture required about 20 times more P in the soil solution for good growth than when grown in the field. These authors also studied the effect of soil volume per plant on corn growth and response to applied P using containers holding 4, 8, 16, 32, and 64 kg of soil. They reported that concentrations of P in plants increased both with increased amounts of added P and increased volumes of soil; plant response to added P increased with decreased volume of soil per plant.

In summary, many factors can influence the correlation between greenhouse and field experiments. Information on most of these factors is scarce and their relevancy to crop performance in strict quantitative terms cannot be assessed accurately. For soils marginally supplied with P, such as the Inceptisol in this investigation, differences in volume of soil per plant may have contributed markedly to the lack of correlation between greenhouse and field results. Plant roots can grow laterally or vertically into more soil and minimize the effect of a restricted P supply under field conditions. For the Oxisol, the lack of agreement between field and greenhouse data may have been caused by other soil factors as discussed previously.

SUMMARY AND CONCLUSIONS

Three tropical soils and a Florida Spodosol were used in this investigation. An Oxisol was collected at Izabal, Guatemala. The top 20-cm layer of this soil had a clay-loam texture; acid reaction (pH of 5.4 in water); 3.5% organic matter; low content of Mehlich- and Bray-extractable P (7.0 and 3.5 ppm, respectively); approximately 3 meq/100 g each of exchangeable Ca and Mg; low content of exchangeable K (0.12 meq/100 g); and clay fraction dominated by kaolinite but with smaller amounts of gibbsite and perhaps Al-interlayered vermiculite present. The top 15-cm layer of an Inceptisol, also collected at Izabal, Guatemala, exhibited a clay-loam texture; pH of 6.4; organic matter content of 7.6%; little extractable P; very high content of exchangeable Mg (39.6 meq/100 g), and Ca and K levels of 6.8 and 0.4 meq/100 g, respectively; with kaolinite as the main crystalline clay component. An Entisol collected at Los Diamantes, Costa Rica, showed the following properties in the top 15 cm: sandy-loam texture; pH of 5.8; 6.3% organic matter; 7.3 and 44.5 ppm of P extracted with Mehlich's and Bray's reagent, respectively; high content of exchangeable K (1.3 meq/100 g), and Ca and Mg levels of 6.0 and 1.9 meq/100 g, respectively; with predominance of poorly crystalline materials in the clay fraction. The Florida Spodosol was collected at the Beef Research Unit, University of Florida, Gainesville, Florida. The top 15-cm layer had a sandy texture; pH of 4.6; 2.9%

organic matter; low content of extractable P, 0.5 meq/100 g of K, and was poorly supplied with Ca and Mg (0.7 and 0.1 meq/100 g, respectively).

Phaseolus lathyroides was grown in the greenhouse on the three tropical soils to assess their fertility status. This legume responded favorably on all soils to a simultaneous application of all major (with the exception of N), secondary, and micronutrients. This response was due mostly to the applied P. For the Oxisol, applications of K and B increased plant growth. For the Inceptisol, Mn and Ca applications reduced dry-matter yields. For the Oxisol and Entisol, application of all nutrients excluding P markedly depressed yields, compared with the control, indicating the importance of a balanced plant nutrition.

Growth response to application of K to the Oxisol was obtained even though the concentration of this element was 1.84% in plant tops from the unfertilized control; this value was much higher than 0.75% K cited as critical concentration for P. lathyroides by Andrew and Robins (18). Calcium concentrations in plant tops from the Inceptisol were relatively low (0.83 to 1.07%), probably caused by the high content of Mg in the soil; K concentrations, however, were relatively high (1.71 to 3.94%), suggesting that high Mg levels in this soil had a greater antagonistic effect on Ca than on K uptake by P. lathyroides. The lack of positive growth response to application of Ca to the Inceptisol indicated that the low Ca concentration found in plant tops from this soil were not related to a deficiency condition. Manganese concentration in plant tops from the unfertilized Oxisol was 1,110 ppm, indicating large amounts of available Mn. Phosphorus fertilization markedly increased K concentrations in plant tops for all soils; this effect may have been due to a better developed root system when P was applied; applied K effects on Ca and Mg uptake were not consistent among soils and plant species. The Oxisol had very large Mg/K ratios due to its high Mg and low K content; plants from this soil responded positively to K fertilization. On the other hand, plants from the Inceptisol, with Mg/K ratios as large as 140, but apparently well supplied with K, did not respond to K fertilization; nor did plants from the Entisol respond to Mg application with Mg/K ratios of 1.5. Some evidence suggested, however, that dissolution of Mg silicate by the neutral NH_4OAc reagent may have contributed to overestimate the amount of exchangeable Mg present in the serpentine-derived Inceptisol.

Centrosema _pubescens_ and _T_. _repens_ were grown on an Oxisol and Spodosol with four rates each of lime and applied P. Lime was applied at rates of 0, 600, 1,200, and 1,800 ppm of reagent-grade $CaCO_3$; P was applied at 0, 25, 50, and 75 ppm. For the Oxisol, legume responses indicated that there was a significant interaction between lime and applied P. Growth of _Centrosema_ increased when the Oxisol was limed with 600 ppm, but yields were depressed at higher rates. The magnitude of plant response to application of 600 ppm of $CaCO_3$ increased with increased rates of applied P. On the other hand, the magnitude of lime-induced yield depressions decreased with increased rates of applied P, suggesting reduced P availability associated with lime rates higher than 600 ppm. For the Oxisol, _T_. _repens_ responses to lime and applied P were similar to those of _Centrosema_. However, _T_. _repens_ yields were depressed to a lesser degree by lime rates higher than

600 ppm; furthermore, liming without applied P consistently depressed yields of T. repens.

For the Spodosol, dry-matter yields increased with increased lime rates through 1,200 ppm of $CaCO_3$; thereafter, yields of Centrosema decreased slightly and those of T. repens remained constant. Trifolium repens failed to grow on the unlimed Spodosol, but Centrosema grew to some extent.

Effects of lime and applied P on concentration and total content of N in Centrosema and T. repens herbage were generally associated with differences in dry-matter production. For the Oxisol, N concentrations ranged from 2.80 to 4.34% in Centrosema and from 3.50 to 4.17% in T. repens. For the Spodosol, N in both legumes varied from 1.91 to 3.42% and from 1.83 to 3.91%, respectively. For the Oxisol, average P concentrations in Centrosema and T. repens herbage increased from 0.12 for the control to 0.22% when 150 ppm of P were applied. For the Spodosol, P concentrations in the legumes increased from 0.15 and 0.14% from untreated soil to 0.80 and 0.68%, respectively, when 150 ppm of P were applied. Liming decreased P concentrations in T. repens from the Spodosol but had no significant effect otherwise. Changes in herbage K concentrations were generally due to dilution or concentration effects caused by changes in dry-matter production. For the Oxisol, K concentrations ranged from 1.00 to 1.71% in Centrosema and from 1.77 to 3.85% in T. repens. For the Spodosol, K in both legumes varied from 1.45 to 3.07% and from 3.90 to 4.41%, respectively. Potassium concentrations in roots were generally one-half to one-third those in plant tops.

Liming consistently increased Ca concentrations in plant tops and roots. On the other hand, P applied to the Oxisol decreased average Ca concentrations from 2.43% in plants from unfertilized soil to 2.12% when 150 ppm of P were applied. This effect, however, was associated with a simultaneous increase in dry-matter yields. For the Spodosol, Ca in legume tops increased from 2.01% from unfertilized soil to 2.17% from soil fertilized with 150 ppm of P. Calcium concentrations in roots were generally one-third to one-half those in plant tops. Liming had little effect on Mg concentrations in plant tops. On the other hand, P fertilization generally decreased Mg concentrations. For the Oxisol, Mg concentrations in Centrosema and T. repens herbage decreased from 0.47 and 0.68% from unfertilized soil to 0.38 and 0.56%, respectively, when 150 ppm of P were applied. For the Spodosol, Mg in the same legumes decreased from 0.41 and 0.36% from the control to 0.34%, respectively, on soil fertilized with 150 ppm of P. Magnesium concentrations in roots were similar or slightly lower than in plant tops.

Liming had a marked negative effect on Mn concentrations in plant tops. Manganese concentrations also decreased with increased rates of P; these effects, however, were generally confounded with growth effects. For the Oxisol, Mn concentrations in Centrosema and T. repens herbage decreased from 324 ppm from untreated soil to 34 ppm when 1,800 ppm of $CaCO_3$ and 150 ppm of P were applied. Lime and applied P had no consistently significant effects on Cu concentrations in both legumes. Copper concentrations in legume herbage ranged from 5 to 14 ppm for the Oxisol and from 4 to 24 ppm for the Spodosol. Lime and applied P decreased Zn concentrations in plant tops, but these effects were generally confounded with growth effects. For the Oxisol, Zn concentrations in Centrosema and T. repens herbage decreased from 180 and 80 ppm from untreated soil to 40 and 30 ppm, respectively, when the highest rates of lime and P were applied. For the Spodosol, Zn concentrations in Centrosema tops decreased from 318 ppm for the control to 65 ppm when 150 ppm of P and 1,800 ppm of $CaCO_3$ were applied. Iron concentrations in plant tops decreased with increased rates of lime and P, but these effects were generally confounded with growth effects. For the Oxisol, the average Fe concentration in Centrosema tops was 277 ppm, and concentrations in T. repens herbage decreased from 876 ppm for the control to 382 ppm in plants from soil receiving the highest rate of lime and P. For the Spodosol, Fe concentrations in the same legumes averaged 184 and 188 ppm, respectively.

In another experiment, P. lathyroides and Siratro were grown consecutively on an Oxisol and Entisol to study the effects of nutrient applications on plant response to liming. Application of all essential plant nutrients (except N, Ca, and Fe) markedly increased dry-matter yields of both legumes. Applied nutrients, however, did not have a significant ameliorating effect on lime-induced yield depressions. Yields were significantly reduced when 5 ppm of Fe-EDDHA were applied with other essential nutrients, suggesting a possible antagonistic effect of Fe or the EDDHA molecule on the uptake of other nutrients. Siratro generally showed higher K, Ca, and Mg concentrations than P. lathyroides.

Three tropical soils and the Florida Spodosol were treated in the laboratory with NaH_2PO_4 solutions to yield final P concentrations in the soil from 0 through 500 ppm; they were subsequently incubated for 72 hours at approximately 25C, and extracted with Bray-P2 reagent. The amount of P extracted from all four soils increased linearly with increased rates of P. The proportion of applied P extracted by the Bray-P2 reagent increased in the following order: Spodosol, Oxisol, Inceptisol, and Entisol. Liming the Oxisol with 1,800 ppm of $CaCO_3$ did not affect significantly the amount of P extracted. The amounts of P extracted from untreated soils were 7.4 ppm for the Inceptisol, 11.9 ppm for the Oxisol, 21.1 ppm for the Spodosol, and 59.6 ppm for the Entisol.

Phosphorus was applied to the three tropical soils in the greenhouse at rates of 0, 50, 100, and 200 ppm of P. For the Inceptisol, 100 ppm of applied P produced maximum _P. lathyroides_ and Siratro herbage yields. Phosphorus concentrations in plant tops from soils fertilized with 100 ppm of P were 0.18% for _P. lathyroides_ and 0.14% for Siratro. For the Oxisol and Entisol, dry-matter yields of _P. lathyroides_ increased linearly with increased rates of P. Phosphorus concentrations in _P. lathyroides_ herbage attained maximum values of 0.18% for the Oxisol and 0.32% for the Entisol at a P rate of 200 ppm.

In general, P fertilization markedly increased K concentrations in plant tops for all soils. On the other hand, the effects of applied P on Ca, Mg, and Zn concentrations were not consistent among soils. Manganese concentrations decreased with increased rates of P. Concentrations of Cu and Fe in legume herbage were generally not affected by applied P.

Two field experiments were established in Izabal, Guatemala, on the Oxisol and Inceptisol, respectively. Phosphorus applied as triple superphosphate at rates of 0, 100, and 200 kg/ha had no significant effect on oven-dry yields of Centrosema, Siratro, and S. humilis. These results were strikingly different from those obtained in the greenhouse using similar soils at equivalent rates of applied P.

For both soils, average P concentrations in Centrosema and Siratro grown in the field increased from 0.23% for the control to 0.28% for soil fertilized with 200 kg/ha of P. Average N concentrations increased from 2.71% in plants from the control to 2.88% when 200 kg/ha of P were applied. Phosphorus fertilization had no significant effects on concentrations of Ca, Mg, Mn, Cu, and Fe in legume herbage. Average Zn concentrations in Centrosema and Siratro tops from the Inceptisol decreased from 53 ppm for the control to 38 ppm for soil fertilized with 200 kg/ha of P. Copper concentrations in legume herbage from the field experiments were higher than those found in plants grown in the greenhouse. On the other hand, Mn concentrations in plants grown under field conditions, particularly on the Oxisol, were markedly lower than concentrations in legumes from the greenhouse.

The following conclusions are presented based on results obtained in these investigations:

1. Phosphorus was the main nutrient limiting plant growth in all three tropical soils. In addition to P, the Oxisol appeared to be deficient in K and B.
2. The Oxisol and Inceptisol showed very high Mg/K and very low Ca/Mg ratios. However, only plants on the Oxisol responded favorably to K or Ca fertilization.
3. For the Oxisol, application of 600 ppm of $CaCO_3$ increased plant growth, but higher lime rates (1,200 and 1,800 ppm) markedly reduced yields.

4. For the Oxisol, there was a significant interaction between effects of lime and applied P on plant growth. Phosphorus fertilization increased plant response to application of 600 ppm of $CaCO_3$, and reduced the magnitude of lime-induced yield depressions. These results suggested reduced P availability induced by lime rates higher than 600 ppm.
5. For the Spodosol, plant response to liming was parabolic with maximum yields at 1,200 ppm of $CaCO_3$.
6. Lime-induced yield depressions were smaller for _T. repens_ than for _Centrosema_, particularly at higher rates of P (50 and 75 ppm). _Trifolium repens_ failed to grow on unlimed Spodosol, but _Centrosema_ grew to some extent.
7. Application of all essential plant nutrients, excluding N and Ca, to an Oxisol and Entisol did not have a significant ameliorating effect on lime-induced yield depressions.
8. Liming invariably increased Ca concentrations in plant tops but did not have a significant effect on P concentrations. Lime effects on K and Mg concentrations were not consistent among soils and plant species.
9. Liming generally decreased Mn and Zn concentrations in plant tops; its effects on Cu and Fe, however, were generally not significant.
10. The effects of P fertilization on herbage N concentrations and uptake were generally confounded with growth effects.
11. Phosphorus fertilization generally increased P and K concentrations in plants. The effects of applied P on Ca and Mg concentrations were not consistent among soils and plant species.

12. Phosphorus applications generally decreased Mn and Zn concentrations in plants; these effects, however, were confounded with dilution effects due to increased yields. The effects of applied P on Cu and Fe concentrations were not consistent among soils and plant species.

13. In greenhouse experiments, *P. lathyroides* and Siratro dry-matter yields increased with increased P rates through 200 ppm for the Oxisol and Entisol, and through 100 ppm for the Inceptisol.

14. In field experiments, however, applied P through 200 kg/ha did not affect oven-dry *Centrosema*, Siratro, and *S. humilis* herbage yields.

15. The lack of agreement between greenhouse and field results may have been caused by some soil factors unidentifiable from data obtained in these investigations. Some possible factors that may account for this differential plant response to applied P are: greater demand for P by plants growing in smaller volumes of soil in pots; chemical changes caused by soil drying resulting in lower P availability; effect of applied P on reducing high plant Mn uptake from the Oxisol, which was observed in the greenhouse but not in the field; microbiological changes caused by soil drying and fumigation, particularly in relation to mycorrhiza development and growth of P-dissolving microorganisms.

APPENDIX

Table 44. Crystalline clay minerals recognized from X-ray diffraction patterns from an Oxisol, Inceptisol, and Entisol.

Soil horizon	Soil depth	Crystalline minerals*
	cm	
		Oxisol
A1	0-20	K_1, G_3, V_2, Q_1
B21	20-50	K_1, G_3, V_3, Q_2
B22	50-125	K_1, V_3, Q_2
		Inceptisol
A1	0-15	K_2, Q_2
B2	15-45	K_2, Q_2
B3	45-125	K_2, Q_1
		Entisol
A1	0-15	Q_2
B2	15-45	Q_3, F_2

* K= kaolinite; G= gibbsite; V= Al-interlayered vermiculite Q= quartz; F= feldspars. Subscript numbers indicate relative intensities with 1 being the highest, 2 intermediate, and 3 lowest.

Table 45. Effects of lime and P applied to an Oxisol and Spodosol on soil pH, liming experiment 1.

P applied	$CaCO_3$ applied, ppm			
	0	600	1,200	1,800
	pH*			
		Oxisol		
0	5.6	5.9	6.4	6.8
75	5.7	6.1	6.6	6.7
Mean	5.6	6.0	6.5	6.8
		Spodosol		
0	4.7	5.4	6.0	6.4
75	5.0	5.8	6.2	6.5
Mean	4.9	5.6	6.1	6.5

* 1:2.5 soil-water ratio.

Table 46. Lime requirement determinations for three experimental soils.

0.05N $Ba(OH)_2$ added	$CaCO_3$ equivalent	Soils		
		Oxisol	Entisol	Spodosol
meq/100 g	ppm	pH*		
0.0	0	5.6	6.0	5.3
0.2	110	5.8	6.1	5.4
0.4	225	6.0	6.3	5.5
0.8	450	6.2	6.5	5.8
1.6	895	6.5	6.6	6.0
3.2	1,790	7.0	6.9	6.6

* 1:2.5 soil-solution ratio.

Table 47. Summaries of the analyses of variance of data shown in Table 13.

Sources	df	Plant responses				
		Yields	P	K	Ca	Mg
		Mean squares				
			Oxisol			
Treatments	11	1.608 **	0.00938 **	1.58814 **	0.36930 **	0.01826 **
Error	24	0.039	0.00105	0.05796	0.05635	0.00178
Total	35	0.532	0.00367	0.53887	0.15471	0.00696
			Entisol			
Treatments	11	1.089 **	0.00623 **	2.16342 **	0.17075 **	0.01258 *
Error	24	0.224	0.00192	0.18247	0.04093	0.00562
Total	35	0.496	0.00328	0.80505	0.08173	0.00781

** Significant F test at the 1% level.

Table 48. Summaries of the analyses of variance of data shown in Table 14.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
			Oxisol		
Treatments	11	237,005.3 **	4.4 NS	617.7 **	12,766.0 NS
Error	24	920.0	2.2	92.3	17,628.9
Total	35	75,118.2	2.9	257.4	16,100.6
			Entisol		
Treatments	11	6,782.3 **	18.1 **	1,633.6 **	17,611.4 NS
Error	24	2,074.9	5.0	108.9	10,330.7
Total	35	3,554.4	9.1	588.1	12,618.9

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 49. Summaries of the analyses of variance of data shown in Table 15.

Sources	df	Plant responses				
		Yields	P	K	Ca	Mg
		Mean squares				
			Herbage			
Treatments	11	1.451 **	0.00650 **	1.00276 **	0.02779 **	0.04619 **
Error	24	0.084	0.00049	0.23908	0.00617	0.00813
Total	35	0.513	0.00238	0.47910	0.01296	0.02009
			Roots			
Treatments	11	0.056 **	0.00437 **	0.37627 **	0.04689 **	0.08658 **
Error	24	0.018	0.00022	0.01857	0.00242	0.00675
Total	35	0.030	0.00153	0.13099	0.01640	0.03184

** Significant F test at the 5% level.

Table 50. Summaries of the analyses of variance of data shown in Table 16.

		Plant responses			
Sources	df	Mn	Cu	Zn	Fe
		------------------------------Mean squares------------------------------			
			Herbage		
Treatments	11	2,612.7 **	0.8 NS	95.7 NS	9,305.1 NS
Error	24	232.8	0.5	110.8	16,287.4
Total	35	980.8	0.6	106.1	14,092.9
			Roots		
Treatments	11	932.7 **	5.7 **	1,124.4 **	123,080.4 **
Error	24	46.6	1.8	281.6	23,435.1
Total	35	325.8	3.0	546.5	54,752.2

** Significant F test at the 5% level.

Table 51. Effects of lime and P applied to an Oxisol and Spodosol on oven-dry Centrosema and T. repens herbage yields from the first planting.

$CaCO_3$ applied ppm	P applied, ppm				
	0	25	50	75	Mean
	Herbage, g/pot				
			Oxisol (Centrosema)		
0	2.0 bcd*	5.0 d	8.3 e	10.4 fg	6.4
600	3.1 cd	8.5 ef	12.0 gh	13.5 h	9.3
1,200	0.5 a	1.0 ab	4.3 d	8.0 e	3.4
1,800	1.2 abc	0.9 ab	3.4 d	6.0 d	2.9
Mean	1.9	3.0	7.0	9.5	5.4
			Oxisol (T. repens)		
0	6.4 bc	7.7 cd	8.5 de	11.8 gh	8.6
600	2.3 a	7.5 cd	13.3 hi	13.7 i	9.2
1,200	2.7 a	5.5 b	10.0 ef	10.6 fg	7.2
1,800	1.5 a	6.3 bc	8.6 de	9.3 def	6.4
Mean	3.2	6.8	10.1	11.4	7.9
			Spodosol (Centrosema)		
0	0.9 a	1.8 abc	1.1 a	1.4 ab	1.3
600	2.9 bcd	2.9 bcd	4.0 d	3.2 cd	3.3
1,200	5.9 e	5.9 e	6.5 ef	8.0 f	6.6
1,800	3.3 cd	5.9 e	7.5 ef	7.0 ef	5.9
Mean	3.3	4.1	4.8	4.9	4.3
			Spodosol (T. repens)		
0	0.0 a	0.0 a	0.0 a	0.0 a	0.0
600	1.7 bc	1.8 bcd	2.3 cde	1.7 bc	1.9
1,200	2.2 cde	2.4 cde	3.0 e	3.0 e	2.7
1,800	1.2 b	2.5 cde	3.1 e	2.7 de	2.4
Mean	1.3	1.7	2.1	1.9	1.8

* Numbers within soil-legume groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 52.

Table 52. Summaries of the analyses of variance of data shown in Table 51.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	86.526 **	159.101 **	6.964 **	1.455 **
Linear	1	23.010 **	73.150 **	4.770 *	0.960 *
Quadratic	1	177.661 **	209.783 **	9.317 **	3.209 NS
Cubic	1	58.906 **	194.370 **	6.803 **	0.195 NS
Lime L	3	145.155 **	19.418 **	71.408 **	17.167 **
Linear	1	251.945 **	44.118 **	176.645 **	37.525 **
Quadratic	1	23.942 **	5.810 *	20.672 **	13.975 **
Cubic	1	159.577 **	8.325 **	16.907 **	0.002 NS
P X L	9	8.740 **	7.828 **	2.623 **	0.475 *
Replications	2	4.156 NS	2.290 NS	5.648 **	0.476 NS
Error	30	1.254	0.936	0.707	0.206
Total	47	17.439	13.589	6.196	1.431

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 53. Effects of lime and P applied to an Oxisol and Spodosol on N concentrations in oven-dry Centrosema and T. repens herbage from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Herbage N, %				
	Oxisol (Centrosema)				
0	4.11 hi*	4.34 i	3.60 def	3.79 fg	3.96
600	3.65 efg	3.46 cde	2.80 a	2.97 ab	3.22
1,200	3.92 gh	3.71 efg	3.37 cd	3.22 bc	3.56
1,800	3.82 fg	3.82 fg	3.38 cd	3.10 b	3.53
Mean	3.88	3.83	3.29	3.27	3.57
	Oxisol (T. repens)				
0	4.25 de	4.38 ef	4.04 cd	3.86 c	4.13
600	4.77 g	4.50 fg	4.06 cd	3.90 c	4.31
1,200	4.36 ef	4.17 de	4.21 de	3.82 bc	4.14
1,800	4.02 cd	3.50 a	3.86 c	3.63 ab	3.75
Mean	4.35	4.14	4.04	3.80	4.08
	Spodosol (Centrosema)				
0	2.91 def	2.75 cde	3.35 f	3.41 f	3.11
600	3.42 f	3.15 ef	2.74 cde	3.02 ef	3.08
1,200	2.96 ef	2.82 cdef	2.24 abc	2.10 ab	2.53
1,800	2.64 bcde	2.36 abcd	2.12 ab	1.91 a	2.26
Mean	2.98	2.77	2.61	2.61	2.74
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	2.78 c	3.83 gh	3.66 g	3.91 h	3.55
1,200	2.22 b	3.42 ef	3.13 d	3.43 f	3.05
1,800	1.83 a	3.06 d	3.24 def	3.19 de	2.83
Mean	2.28	3.44	3.34	3.51	3.14

* Numbers within soil-legume groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 67.

** Insufficient plant material for chemical analysis.

Table 54. Effects of lime and P applied to an Oxisol and Spodosol on N contents in oven-dry *Centrosema* and *T. repens* herbage from the first planting.

CaCO$_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Herbage N, mg/pot				
Oxisol (*Centrosema*)					
0	110 b*	218 ef	299 gh	394 hi	255
600	114 b	292 g	336 ghi	401 i	286
1,200	21 a	39 a	145 cd	258 ef	116
1,800	45 ab	35 a	115 c	186 cd	95
Mean	75	146	224	310	188
Oxisol (*T. repens*)					
0	272 bc	335 cd	344 cd	455 ef	352
600	111 a	336 cd	539 g	534 fg	380
1,200	120 a	229 b	424 e	406 de	295
1,800	59 a	221 b	332 cd	338 cd	238
Mean	141	280	410	433	316
Spodosol (*Centrosema*)					
0	27	51	36	47	40 m
600	100	92	110	97	100 n
1,200	172	168	145	169	164 p
1,800	88	136	158	132	129 o
Mean	97 a	112 a	112 a	111 a	108
Spodosol (*T. repens*)					
0	-**	-	-	-	-
600	48 ab	68 bc	83 cd	66 bc	66
1,200	49 ab	83 cd	95 cd	103 d	83
1,800	21 a	76 bcd	101 d	85 cd	71
Mean	39	76	93	85	73

* Numbers within soil-legume groups not followed by a common letter, groups a-g and m-p, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 68.

** Insufficient plant material for chemical analysis.

Table 55. Summaries of the analyses of variance of data shown in Table 18.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	0.01485 **	0.03248 **	0.84892 **	0.51481 **
Linear	1	0.00082 NS	0.00375 NS	0.49594 **	0.03682 **
Quadratic	1	0.00889 **	0.01805 **	0.20801 **	0.94760 **
Cubic	1	0.03484 **	0.07562 **	1.84281 **	0.56000 **
Lime L	3	0.01086 **	0.00188 NS	0.01262 NS	0.58714 **
Linear	1	0.00353 *	0.00014 NS	0.02838 NS	0.65313 **
Quadratic	1	0.01613 **	0.00008 NS	0.00317 NS	0.94080 **
Cubic	1	0.01291 **	0.00542 NS	0.00631 NS	0.16748 **
P X L	9	0.00070 NS	0.00094 NS	0.02038 NS	0.06842 **
Replications	2	0.00271 *	0.00018 NS	0.01092 NS	0.00661 NS
Error	30	0.00059	0.00146	0.00943	0.00242
Total	47	0.00227	0.00331	0.06538	0.08526

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 56. Summaries of the analyses of variance of data shown in Table 19.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		--------Mean squares--------			
Phosphorus P	3	0.00380 **	0.00826 **	0.15523 **	0.19772 **
Linear	1	0.00004 NS	0.00135 NS	0.09375 **	0.03604 **
Quadratic	1	0.00587 **	0.01502 **	0.13347 **	0.18707 **
Cubic	1	0.00550 **	0.00840 **	0.23847 **	0.37007 **
Lime L	3	0.00691 **	0.00708 **	0.00825 **	0.32757 **
Linear	1	0.00900 **	0.01320 **	0.01411 **	0.31828 **
Quadratic	1	0.01172 **	0.00801 **	0.01021 **	0.58080 **
Cubic	1	0.00001 NS	0.00002 NS	0.00043 NS	0.08363 **
P X L	9	0.00135 *	0.00356 **	0.00353 **	0.03221 **
Replications	2	0.00114 NS	0.00008 NS	0.00086 NS	0.00058 NS
Error	30	0.00049	0.00074	0.00108	0.00035
Total	47	0.00130	0.00214	0.01183	0.03994

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 57. Effects of lime and P applied to an Oxisol and Spodosol on K concentrations in oven-dry Centrosema and T. repens roots from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Root K, %				
		Oxisol (Centrosema)			
0	0.82	0.62	0.61	0.60	0.66 mn
600	0.78	0.45	0.45	0.46	0.54 m
1,200	0.84	0.66	0.83	0.73	0.76 n
1,800	0.85	0.80	0.66	0.56	0.72 n
Mean	0.82 b*	0.63 a	0.64 a	0.59 a	0.67
		Oxisol (T. repens)			
0	0.89 bc	1.01 cd	0.99 cd	0.76 ab	0.91
600	1.16 d	0.75 ab	0.76 ab	0.59 a	0.82
1,200	1.59 e	0.82 bc	0.82 bc	0.58 a	0.95
1,800	1.59 e	0.84 bc	0.75 ab	0.75 ab	0.98
Mean	1.31	0.86	0.83	0.67	0.91
		Spodosol (Centrosema)			
0	0.86 bc	1.00 cde	0.75 ab	0.65 a	0.82
600	1.05 def	1.20 fgh	0.89 bcd	1.28 ghi	1.10
1,200	1.42 ijk	1.29 ghi	1.14 efg	1.52 jk	1.34
1,800	1.07 ef	1.35 hij	1.53 k	1.10 ef	1.26
Mean	1.10	1.21	1.08	1.14	1.13
		Spodosol (T. repens)			
0	-**	-	-	-	-
600	1.68	1.26	1.51	1.35	1.45
1,200	1.74	1.52	1.70	1.85	1.70
1,800	1.66	1.35	1.72	1.77	1.62
Mean	1.69 b	1.38 a	1.64 b	1.66 b	1.59

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-k and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 77.

** Insufficient plant material for chemical analysis.

Table 58. Effects of lime and P applied to an Oxisol and Spodosol on Ca concentrations in oven-dry *Centrosema* and *T. repens* roots from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Root Ca, %				
	Oxisol (Centrosema)				
0	0.88 bcd*	0.63 ab	0.73 abc	0.77 abc	0.75
600	0.95 cde	0.58 a	0.58 a	0.63 ab	0.68
1,200	1.00 cdef	0.55 a	1.20 efg	0.99 cde	0.94
1,800	1.29 fg	1.34 g	1.07 defg	1.07 defg	1.19
Mean	1.03	0.78	0.90	0.86	0.89
	Oxisol (T repens)				
0	0.73	0.60	0.61	0.43	0.59 m
600	0.72	0.64	0.63	0.63	0.66 m
1,200	0.86	0.64	0.61	0.50	0.65 m
1,800	1.11	0.80	0.71	0.67	0.82 n
Mean	0.86 c	0.67 b	0.64 ab	0.56 a	0.68
	Spodosol (Centrosema)				
0	0.36 a	0.37 a	0.51 b	0.72 c	0.49
600	0.73 c	0.57 b	0.60 bc	0.71 c	0.65
1,200	0.74 c	0.93 d	1.00 de	0.72 c	0.85
1,800	1.20 f	1.03 de	1.23 f	1.11 ef	1.14
Mean	0.76	0.72	0.84	0.82	0.78
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	0.74	0.68	0.70	0.76	0.72 m
1,200	0.76	0.69	0.68	0.85	0.74 mn
1,800	0.76	0.83	0.85	0.76	0.80 n
Mean	0.75 a	0.73 a	0.74 a	0.79 a	0.80 n

* Numbers within soil-legume groups not followed by a common letter, within groups a-g and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 78.

** Insufficient plant material for chemical analysis.

Table 59. Effects of lime and P applied to an Oxisol and Spodosol on Mg in oven-dry *Centrosema* and *T. repens* roots from the first planting.

$CaCO_3$ applied ppm	P applied, ppm 0	 25	 50	 75	 Mean
	Root Mg, %				
			Oxisol (*Centrosema*)		
0	0.56 c*	0.29 ab	0.30 ab	0.31 ab	0.36
600	0.54 c	0.29 ab	0.26 a	0.30 ab	0.35
1,200	0.36 ab	0.27 a	0.30 ab	0.29 ab	0.30
1,800	0.36 ab	0.39 b	0.37 ab	0.33 ab	0.36
Mean	0.46	0.31	0.31	0.31	0.35
			Oxisol (*T. repens*)		
0	0.38	0.35	0.29	0.27	0.32 m
600	0.41	0.33	0.37	0.33	0.36 mn
1,200	0.40	0.36	0.35	0.27	0.34 mn
1,800	0.54	0.37	0.32	0.33	0.39 n
Mean	0.43 b	0.35 a	0.33 a	0.30 a	0.35
			Spodosol (*Centrosema*)		
0	0.22	0.23	0.22	0.31	0.24 m
600	0.23	0.26	0.21	0.28	0.24 m
1,200	0.33	0.37	0.40	0.28	0.34 n
1,800	0.46	0.34	0.24	0.36	0.35 n
Mean	0.31 a	0.30 a	0.27 a	0.31 a	0.30
			Spodosol (*T. repens*)		
0	-**	-	-	-	-
600	0.25	0.20	0.21	0.24	0.22 m
1,200	0.22	0.20	0.18	0.23	0.21 m
1,800	0.21	0.19	0.21	0.18	0.20 m
Mean	0.23 a	0.20 a	0.20 a	0.22 a	0.21

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-c and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 79.

** Insufficient plant material for chemical analysis.

Table 60. Effects of lime and P applied to an Oxisol and Spodosol on Mn concentrations in oven-dry Centrosema and T. repens roots from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Root Mn, ppm				
			Oxisol (Centrosema)		
0	530 f*	381 e	185 bc	285 d	345
600	133 ab	223 cd	152 abc	119 ab	157
1,200	131 ab	101 ab	105 ab	116 ab	113
1,800	76 a	98 ab	97 ab	91 a	90
Mean	218	201	135	153	177
			Oxisol (T. repens)		
0	244	189	151	142	182 n
600	162	139	156	155	153 n
1,200	126	80	94	128	107 n
1,800	123	99	84	94	100 m
Mean	164 b	127 a	121 a	130 a	136
			Spodosol (Centrosema)		
0	108 bc	138 cd	217 e	169 d	158
600	70 b	73 b	77 b	99 bc	80
1,200	20 a	28 a	25 a	28 a	25
1,800	24 a	28 a	30 a	22 a	26
Mean	56	67	87	80	72
			Spodosol (T. repens)		
0	-**	-	-	-	-
600	69 e	59 d	69 e	70 e	67
1,200	28 bc	23 ab	19 a	35 c	26
1,800	16 a	23 ab	21 ab	21 ab	20
Mean	38	35	36	42	38

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-e and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 80.

** Insufficient plant material for chemical analysis.

Table 61. Effects of lime and P applied to an Oxisol and Spodosol on Cu concentrations in oven-dry Centrosema and T. repens roots from the first planting.

CaCO$_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Root Cu, ppm				
	Oxisol (Centrosema)				
0	17	14	14	10	14 m
600	14	12	14	11	13 m
1,200	23	10	13	12	14 m
1,800	19	18	11	11	15 m
Mean	18 b*	14 a	13 a	11 a	14
	Oxisol (T. repens)				
0	11 ab	8 a	12 ab	11 ab	10
600	11 ab	13 ab	14 ab	21 c	15
1,200	11 ab	10 ab	10 ab	10 ab	10
1,800	12 ab	15 bc	11 ab	10 ab	12
Mean	11	12	12	13	12
	Spodosol (Centrosema)				
0	22 f	18 e	18 e	25 g	21
600	16 cde	15 cd	14 bc	16 cde	15
1,200	16 cde	15 cd	17 de	21 f	17
1,800	10 a	12 b	12 b	15 cd	12
Mean	16	15	15	19	16
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	21 f	12 bc	15 d	17 e	16
1,200	9 a	12 bc	11 ab	14 cd	12
1,800	9 a	13 bcd	12 bc	12 bc	12
Mean	13	12	13	14	13

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-g and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 81.

** Insufficient plant material for chemical analysis.

Table 62. Effects of lime and P applied to an Oxisol and Spodosol on Zn concentrations in oven-dry Centrosema and T. repens roots from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Root Zn, ppm				
	Oxisol (Centrosema)				
0	77	47	38	35	49 m
600	47	34	38	40	40 m
1,200	38	41	52	36	42 m
1,800	45	43	31	32	38 m
Mean	52 b*	41 ab	40 ab	36 a	42
	Oxisol (T. repens)				
0	130 g	128 g	116 efg	134 g	127
600	121 fg	86 cd	98 def	84 bcd	97
1,200	94 de	62 ab	62 ab	70 abc	72
1,800	51 a	71 abc	55 a	48 a	56
Mean	99	87	83	84	88
	Spodosol (Centrosema)				
0	183	133	157	171	161 o
600	141	84	78	111	104 n
1,200	73	68	67	59	67 m
1,800	54	59	49	63	56 m
Mean	113 b	86 a	88 a	101 ab	97
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	129 de	123 de	117 d	138 e	127
1,200	72 c	66 bc	48 ab	83 c	67
1,800	51 ab	45 a	66 bc	51 ab	54
Mean	84	78	77	91	82

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-g and m-o, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 82.

** Insufficient plant material for chemical analysis.

Table 63. Effects of lime and P applied to an Oxisol and Spodosol on Fe concentrations in oven-dry Centrosema and T. repens roots from the first planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Root Fe, ppm				
	Oxisol (Centrosema)				
0	5,951	18,322	15,118	4,018	10,852 m
600	4,683	13,573	4,106	12,628	8,748 m
1,200	11,666	6,723	6,331	5,891	7,653 m
1,800	9,379	5,228	12,334	5,279	8,055 m
Mean	7,920 a*	10,962 a	9,472 a	6,954 a	8,827
	Oxisol (T. repens)				
0	2,086	3,868	6,102	3,123	3,795 m
600	4,515	21,039	14,851	6,337	11,686 m
1,200	9,055	3,428	6,150	1,803	5,109 m
1,800	9,323	18,875	1,798	4,524	8,630 m
Mean	6,245 a	11,802 a	7,225 a	3,947 a	7,305
	Spodosol (Centrosema)				
0	612	493	616	999	680 m
600	1,590	1,278	676	455	1,000 m
1,200	362	438	482	355	409 m
1,800	2,247	507	582	375	928 m
Mean	1,203 a	679 a	589 a	546 a	754
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	315	314	417	422	367 n
1,200	287	220	194	340	260 m
1,800	315	221	213	286	259 m
Mean	306 bc	252 a	275 ab	349 c	295

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-c and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 83.

** Insufficient plant material for chemical analysis.

Table 64. Effects of lime and P applied to an Oxisol and Spodosol on Al concentrations in oven-dry Centrosema and T. repens roots from the first planting.

$CaCO_3$ applied ppm	P applied, ppm				
	0	25	50	75	Mean
	Root Al, ppm				
	Oxisol (Centrosema)				
0	5,771	12,996	4,897	4,018	6,920 m
600	4,614	8,356	7,316	12,628	8,228 m
1,200	11,240	3,880	4,730	5,891	6,435 m
1,800	7,743	7,861	7,511	5,279	7,098 m
Mean	7,342 a*	8,273 a	6,114 a	6,954 a	7,171
	Oxisol (T. repens)				
0	3,603	2,410	4,487	2,624	3,281 mn
600	3,620	5,483	7,623	3,575	5,075 n
1,200	2,218	1,717	3,086	3,649	2,668 m
1,800	5,696	8,851	3,073	2,811	5,108 n
Mean	3,784 a	4,615 a	4,567 a	3,165 a	4,033
	Spodosol (Centrosema)				
0	703 g	515 def	662 fg	936 h	704
600	896 h	447 cde	550 efg	421 cde	578
1,200	235 ab	353 bcd	415 cde	293 abc	324
1,800	530 ef	384 bcde	190 a	408 cde	378
Mean	591	425	454	514	496
	Spodosol (T. repens)				
0	-**	-	-	-	-
600	341	371	418	375	376 n
1,200	278	208	188	235	227 m
1,800	179	178	188	198	186 m
Mean	266	252	265	269	263

* Numbers within soil-legume groups not followed by a common letter, within letter groups a-h and m-n, are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 84.

** Insufficient plant material for chemical analysis.

Table 65. Effects of lime and P applied to an Oxisol and Spodosol on oven-dry *Centrosema* herbage yields from the second planting.

$CaCO_3$ applied	P applied, ppm				
	0	25	50	75	Mean
ppm	Herbage, g/pot				
			Oxisol		
0	0.4 a*	2.0 de	3.2 f	2.3 a	2.0
600	2.0 de	2.4 e	2.3 e	1.7 cd	2.1
1,200	1.1 b	0.5 a	0.5 a	1.2 bc	0.8
1,800	0.2 a	0.7 ab	0.7 ab	1.7 cd	0.8
Mean	0.9	1.4	1.7	1.7	1.4
			Spodosol		
0	1.4 ab	1.1 ab	0.8 a	1.2 ab	1.1
600	1.7 bc	2.4 d	2.4 d	2.1 cd	2.2
1,200	1.4 ab	1.3 ab	1.0 a	1.4 ab	1.3
1,800	1.0 a	1.7 bc	1.0 a	1.2 ab	1.2
Mean	1.4	1.6	1.3	1.5	1.4

* Numbers within soil groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 66.

Table 66. Summaries of the analyses of variance shown in Table 65.

Sources	df	Soils Oxisol	 Spodosol
		Mean squares	
Phosphorus P	3	1.637 **	0.211 NS
Linear	1	1.215 **	0.282 NS
Quadratic	1	2.276 **	0.320 NS
Cubic	1	1.420 **	0.031 NS
Lime L	3	5.197 **	2.730 **
Linear	1	13.490 **	0.210 NS
Quadratic	1	0.075 NS	3.360 **
Cubic	1	4.187 **	4.620 **
P X L	9	1.433 **	0.226 *
Replications	2	0.035 NS	0.063 NS
Error	30	0.075	0.092
Total	47	0.806	0.292

* Significant F test at the 5% level.
** Significant F test at the 1% level.

Table 67. Summaries of the analyses of variance of data shown in Table 53.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	1.32672 **	0.61832 **	0.37122 *	2.27175 **
Linear	1	0.01084 NS	0.27094 **	0.27094 NS	4.53270 **
Quadratic	1	2.56511 **	0.32401 **	0.55651 *	1.06337 **
Cubic	1	1.40422 **	1.26001 **	0.28622 NS	1.21918 **
Lime L	3	1.10548 **	0.66132 **	2.10952 **	30.68624 **
Linear	1	0.54722 **	1.02573 **	5.74742 **	38.37600 **
Quadratic	1	1.53368 **	0.94922 **	0.18750 NS	42.50685 **
Cubic	1	1.23554 **	0.00900 NS	0.39366 NS	11.17585 **
P X L	9	0.05312 *	0.11210 **	0.34001 **	0.28723 **
Replications	2	0.17229 **	0.00261 NS	0.10557 NS	0.00308 NS
Error	30	0.02140	0.01486	0.09894	0.01560
Total	47	0.18641	0.11274	0.29110	2.16879

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 68. Summaries of the analyses of variance of data shown in Table 54.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	73,506.6 **	218,370.1 **	684.2 NS	3,770.8 **
Linear	1	30,602.0 **	115,787.0 **	1,380.2 NS	4,455.4 **
Quadratic	1	139,480.0 **	318,269.0 **	501.4 NS	5,706.7 **
Cubic	1	50,437.7 **	221,056.7 **	171.2 NS	1,150.3 *
Lime L	3	153,511.2 **	48,591.8 **	32,599.2 **	16,677.1 **
Linear	1	345,117.5 **	111,629.1 **	64,517.6 **	31,625.1 **
Quadratic	1	3,485.0 NS	22,274.1 **	27,027.5 **	18,135.2 **
Cubic	1	111,931.2 **	11,872.3 *	6,252.6 **	250.9 NS
P X L	9	7,030.3 **	12,483.3 **	970.3 NS	721.4 **
Replications	2	1,362.5 NS	4,585.3 NS	4,242.9 **	521.4 NS
Error	30	1,130.5	1,855.0	510.1	224.1
Total	47	16,616.3	20,809.8	2,816.4	1,608.5

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 69. Summaries of the analyses of variance of data shown in Table 20.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	0.43732 **	4.60221 **	0.28843 **	0.08412 NS
Linear	1	0.40560 **	3.21202 **	0.02220 NS	0.10667 NS
Quadratic	1	0.23805 **	5.17347 **	0.79170 **	0.00002 NS
Cubic	1	0.66831 **	5.42114 **	0.05138 NS	0.14567 NS
Lime L	3	0.50362 **	0.37592 **	2.93976 **	50.54352 **
Linear	1	0.62730 **	0.15100 NS	8.50514 **	86.56808 **
Quadratic	1	0.41627 **	0.02168 NS	0.30401 **	54.57068 **
Cubic	1	0.46728 **	0.95508 **	0.01014 NS	10.49180 **
P X L	9	0.05615 **	0.48754 **	0.08604 **	0.03913 NS
Replications	2	0.00443 NS	0.05171 NS	0.11883 **	0.07548 NS
Error	30	0.01740	0.04248	0.01485	0.07411
Total	47	0.08211	0.44043	0.23707	3.28956

** Significant F test at the 1% level.

Table 70. Summaries of the analyses of variance of data shown in Table 21.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	0.20189 NS	0.29728 **	0.20496 **	0.26990 **
Linear	1	0.09250 NS	0.00375 NS	0.07594 NS	0.44554 **
Quadratic	1	0.15217 NS	0.43245 **	0.44023 **	0.18707 **
Cubic	1	0.36100 NS	0.45562 **	0.09870 *	0.17710 *
Lime L	3	3.35266 **	0.82128 **	6.03382 **	13.81527 **
Linear	1	10.05732 **	2.46038 **	15.39760 **	32.06897 **
Quadratic	1	0.00025 NS	0.00008 NS	2.30125 **	7.99517 **
Cubic	1	0.00040 NS	0.00338 NS	0.40262 **	1.38168 **
P X L	9	0.00649 NS	0.01141 NS	0.03977 NS	0.07257 *
Replications	2	0.04072 NS	0.18582 *	0.02618 NS	0.01389 NS
Error	30	0.09517	0.03603	0.02297	0.02453
Total	47	0.29061	0.10449	0.42161	0.92920

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 71. Summaries of the analyses of variance of data shown in Table 22.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	0.02047 **	0.05092 **	0.01142 **	0.00098 NS
Linear	1	0.00454 NS	0.01354 NS	0.01042 *	0.00240 NS
Quadratic	1	0.04061 **	0.02531 NS	0.01560 *	0.00005 NS
Cubic	1	0.01626 **	0.11391 **	0.00825 NS	0.00051 NS
Lime L	3	0.01342 **	0.00557 NS	0.21991 **	0.37226 **
Linear	1	0.01785 **	0.00165 NS	0.57722 **	0.52173 **
Quadratic	1	0.00017 NS	0.00677 NS	0.07922 **	0.45825 **
Cubic	1	0.02223 NS	0.00828 NS	0.00330 NS	0.13680 **
P X L	9	0.00318 NS	0.00890 NS	0.00217 NS	0.00169 NS
Replications	2	0.02098 **	0.00193 NS	0.00061 NS	0.00001 NS
Error	30	0.00214	0.01039	0.00246	0.00091
Total	47	0.00503	0.01202	0.01678	0.02473

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 72. Summaries of the analyses of variance of data shown in Table 23.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	1,193.0 **	7,747.7 **	5,935.9 **	91.7 NS
Linear	1	253.5 *	4,873.5 **	782.0 NS	12.0 NS
Quadratic	1	2,964.5 **	5,202.0 **	11,425.7 **	15.1 NS
Cubic	1	361.0 *	13,167.6 **	5,600.0 **	248.1 NS
Lime L	3	14,241.0 **	42,363.2 **	150,222.8 **	66,704.7 **
Linear	1	41,501.4 **	122,718.0 **	418,335.0 **	218.5 NS
Quadratic	1	1.200.0 **	3,942.2 **	363.0 NS	104,813.5 **
Cubic	1	21.6 NS	429.3 NS	31,970.4 **	95,082.2 **
P X L	9	108.3 NS	367.2 NS	1,669.0 **	144.5 NS
Replications	2	1,860.2 **	169.2 NS	495.4 NS	62.5 NS
Error	30	50.5	208.1	284.5	78.1
Total	47	1,117.3	3,408.9	10,489.8	4,343.8

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 73. Summaries of the analyses of variance of data shown in Table 24.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centresema	T. repens
		---Mean squares---			
Phosphorus P	3	21.6 *	12.4 *	7.8 NS	30.8 **
Linear	1	0.4 NS	35.0 *	9.4 NS	70.0 **
Quadratic	1	33.3 *	0.3 NS	0.1 NS	19.0 NS
Linear	1	31.2 *	1.8 NS	14.0 NS	3.4 NS
Lime L	3	16.8 NS	3.3 NS	311.6 **	479.4 **
Linear	1	5.1 NS	0.8 NS	924.3 **	98.8 **
Quadratic	1	15.2 NS	3.0 NS	9.2 NS	1,083.0 **
Cubic	1	30.1 NS	6.0 NS	1.2 NS	256.3 **
P X L	9	14.6 NS	7.7 NS	10.2 NS	8.3 NS
Replications	2	1.5 NS	10.9 NS	3.8 NS	3.6 NS
Error	30	7.1	5.2	5.2	5.0
Total	47	9.9	6.2	25.8	37.5

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 74. Summaries of the analyses of variance of data shown in Table 25.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	6,230.0 **	628.8 **	5,373.3 **	699.6 **
Linear	1	3,313.5 **	294.0 NS	1,350.0 NS	1,350.2 **
Quadratic	1	8,320.5 **	722.0 **	4,257.6 **	430.2 **
Cubic	1	7,056.0 **	870.2 **	4,257.6 **	348.4 **
Lime L	3	6,740.0 **	1,530.1 **	76,739.6 **	22,402.5 **
Linear	1	12,441.6 **	4,386.2 **	169,548.5 **	3,603.8 **
Quadratic	1	6,912.0 **	0.8 NS	53,266.7 **	43,802.1 **
Cubic	1	866.4 **	205.4 NS	7,403.7 **	19,801.7 **
P X L	9	2,310.0 **	90.8 NS	3,223.9 **	175.2 **
Replications	2	1,556.3 **	199.6 NS	64.7 NS	27.1 NS
Error	30	86.2	83.6	445.7	49.1
Total	47	1,391.5	217.0	6,145.8	1,540.6

** Significant F test at the 1% level.

Table 75. Summaries of the analyses of variance of data shown in Table 26.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	15,829.4 NS	42,132.4 *	3,218.0 **	811.0 NS
Linear	1	11,051.0 NS	87,604.2 *	7,315.0 **	57.0 NS
Quadratic	1	4,753.1 NS	5,547.6 NS	19.0 NS	2,369.0 NS
Cubic	1	31,684.0 NS	33,245.4 NS	2,320.0 NS	7.1 NS
Lime L	3	2,106.4 NS	53,732.4 *	15,999.0 **	109,386.0 **
Linear	1	493.1 NS	148,802.4 **	46,426.0 **	148,802.4 **
Quadratic	1	5,504.1 NS	6,768.8 NS	1,323.0 NS	128,547.0 **
Cubic	1	322.0 NS	5,626.0 NS	248.1 NS	50,808.6 **
P X L	9	5,537.3 NS	29,665.7 *	400.4 NS	2,566.1 NS
Replications	2	18,649.8 NS	21,590.3 NS	709.1 NS	10,611.4 *
Error	30	8,066.3	12,669.9	651.2	2,243.6
Total	47	8,147.5	20,805.6	1,749.1	9,408.9

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 76. Summaries of the analyses of variance of data shown in Table 17.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	8.939 **	45.446 **	0.084 NS	3.288 **
Linear	1	0.667 NS	17.682 **	0.010 NS	9.250 **
Quadratic	1	6.125 **	45.125 **	0.023 NS	0.587 NS
Cubic	1	20.026 **	73.531 **	0.218 NS	0.028 NS
Lime L	3	12.676 **	39.916 **	2.318 **	14.251 **
Linear	1	6.700 **	19.437 **	3.750 **	31.683 **
Quadratic	1	10.735 **	28.985 **	3.100 **	10.830 **
Cubic	1	20.592 **	50.325 **	0.101 NS	0.241 NS
P X L	9	1.584 **	4.090 **	0.101 NS	0.950 **
Replications	2	0.511 NS	0.744 NS	1.040 **	0.253 NS
Error	30	0.470	0.494	0.118	0.192
Total	47	2.005	6.132	0.292	1.435

** Significant F test at the 1% level.

Table 77. Summaries of the analyses of variance of data shown in Table 57.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		---Mean squares---			
Phosphorus P	3	0.12778 **	0.90773 **	0.04095 *	0.13999 *
Linear	1	0.21470 **	1.25127 **	0.07482 **	0.33370 **
Quadratic	1	0.06301 NS	0.50334 **	0.04702 *	0.05173 NS
Cubic	1	0.10562 *	0.96858 **	0.00100 NS	0.03453 NS
Lime L	3	0.11938 **	0.06569 **	0.64830 **	7.73236 **
Linear	1	0.09283 NS	0.07526 *	1.49468 **	15.76450 **
Quadratic	1	0.02083 NS	0.05005 *	0.40700 **	6.98450 **
Cubic	1	0.24448 **	0.07176 *	0.04320 *	0.44807 **
P X L	9	0.01843 NS	0.13187 **	0.11475 **	0.04025 NS
Replications	2	0.00631 NS	0.01741 NS	0.07857 **	0.01488 NS
Error	30	0.02300	0.01147	0.00954	0.03867
Total	47	0.03426	0.09545	0.07540	0.53551

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 78. Summaries of the analyses of variance of data shown in Table 58.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	0.13526 **	0.18627 **	0.03259 **	0.00374 NS
Linear	1	0.39527 **	0.20350 **	0.00634 NS	0.00120 NS
Quadratic	1	0.00036 NS	0.12251 **	0.07540 **	0.00001 NS
Cubic	1	0.01017 NS	0.23281 **	0.01604 *	0.01000 NS
Lime L	3	0.62100 **	0.11890 **	0.94468 **	1.72587 **
Linear	1	1.48365 **	0.28912 **	2.78211 **	3.53322 **
Quadratic	1	0.32505 **	0.03467 NS	0.04941 **	1.33333 **
Cubic	1	0.05430 NS	0.03290 NS	0.00254 NS	0.31104 **
P X L	9	0.09405 **	0.01637 NS	0.05164 **	0.00802 NS
Replications	2	0.01099 NS	0.00716 NS	0.02218 *	0.00276 NS
Error	30	0.02257	0.01263	0.00652	0.00600
Total	47	0.08115	0.03098	0.07737	0.11589

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 79. Summaries of the analyses of variance of data shown in Table 59.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	0.06528 **	0.03679 **	0.00494 NS	0.00124 NS
Linear	1	0.12907 **	0.03760 **	0.00060 NS	0.00282 NS
Quadratic	1	0.04302 **	0.02761 **	0.01227 NS	0.00056 NS
Cubic	1	0.02377 **	0.04516 **	0.00195 NS	0.00034 NS
Lime L	3	0.00889 *	0.00901 *	0.04312 *	0.13338 **
Linear	1	0.00165 NS	0.01926 *	0.10458 NS	0.19494 **
Quadratic	1	0.01577 NS	0.00017 NS	0.00017 NS	0.16568 **
Cubic	1	0.00925 NS	0.00759 NS	0.02460 NS	0.03953 **
P X L	9	0.01464 **	0.00482 NS	0.01250 NS	0.00083 NS
Replications	2	0.00003 NS	0.00058 NS	0.01060 NS	0.00068 NS
Error	30	0.00337	0.00300	0.00629	0.00052
Total	47	0.00969	0.00579	0.00993	0.00911

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 80. Summaries of the analyses of variance of data shown in Table 60.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		-----------Mean squares-----------			
Phosphorus P	3	18,332.1 **	4,484.4 *	2,299.3 *	71.1 *
Linear	1	1,700.2 NS	8,251.0 *	759.4 NS	22.0 NS
Quadratic	1	44,302.7 **	4,688.3 NS	5,321.7 **	0.1 NS
Cubic	1	8,993.4 NS	513.8 NS	817.0 NS	191.4 **
Lime L	3	161,054.8 **	17,946.2 **	47,018.5 **	9,398.6 **
Linear	1	391,718.4 **	50,460.0 **	121,905.3 **	240.0 **
Quadratic	1	82,170.8 **	1,452.0 NS	18,526.0 **	15,914.1 **
Cubic	1	9,275.3 NS	1,926.7 NS	624.0 NS	12,041.7 **
P X L	9	17,883.0 **	1,610.8 NS	1,575.4 *	58.2 *
Replications	2	1,135.6 NS	780.3 NS	82.3 NS	12.8 NS
Error	30	2,265.5	1,207.9	526.5	23.7
Total	47	16,369.0	2,544.5	3,789.2	631.3

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 81. Summaries of the analyses of variance of data shown in Table 61.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	118.9 **	9.6 NS	48.7 **	5.6 NS
Linear	1	140.2 **	0.4 NS	3.4 NS	0.7 NS
Quadratic	1	84.5 *	1.7 NS	0.7 NS	0.1 NS
Cubic	1	132.2 **	26.7 NS	142.0 **	0.2 NS
Lime L	3	7.1 NS	51.1 **	145.8 **	553.4 **
Linear	1	8.8 NS	0.1 NS	324.3 **	522.2 **
Quadratic	1	3.0 NS	21.3 NS	2.5 NS	768.0 **
Cubic	1	9.6 NS	132.0 **	110.7 **	270.0 **
P X L	9	24.9 NS	25.8 *	7.6 *	20.9 **
Replications	2	23.8 NS	10.3 NS	5.4 NS	0.3 NS
Error	30	16.8	10.2	3.0	2.9
Total	47	24.5	15.7	16.0	41.5

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 82. Summaries of the analyses of variance of data shown in Table 62.

		Soil-legume combinations			
		Oxisol		Spodosol	
Sources	df	Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	1,261.5 **	659.9 **	1,904.7 **	271.3 NS
Linear	1	1,837.5 **	864.0 *	4,374.0 **	126.0 NS
Quadratic	1	896.0 *	854.2 *	1,073.4 **	58.7 NS
Cubic	1	1,050.8 **	261.4 NS	266.8 NS	629.2 NS
Lime L	3	438.7 NS	11,520.2 **	27,025.2 **	32,566.5 **
Linear	1	382.5 NS	33,986.4 **	74,483.3 **	5,950.1 **
Quadratic	1	9.2 NS	560.3 NS	6,580.1 **	59,431.7 **
Cubic	1	924.3 NS	14.0 NS	12.2 NS	32,317.6 **
P X L	9	220.0 NS	466.0 *	734.1 NS	284.7 *
Replications	2	160.3 NS	5.4 NS	216.0 NS	34.9 NS
Error	30	213.0	141.1	404.3	96.3
Total	47	293.4	957.1	2,254.5	2,213.5

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 83. Summaries of the analyses of variance of data shown in Table 63.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	47,684,382.0 NS	130,570,770.0 NS	17,028,430.0 NS	12,014.1 *
Linear	1	55,507,375.0 NS	185,337,070.0 NS	21,262,838.0 NS	9,801.0 NS
Quadratic	1	7,917.0 NS	25,864,829.0 NS	19,342,127.0 NS	78.1 NS
Cubic	1	87,537,855.0 NS	180,510,420.0 NS	10,480,327.0 NS	26,163.1 **
Lime L	3	54,902,270.0 NS	152,354,360.0 NS	22,951,370.0 NS	292,953.6 **
Linear	1	129,442,410.0 NS	37,706,361.0 NS	3,046,056.0 NS	268,737.3 **
Quadratic	1	183,027.0 NS	57,310,367.0 NS	14,614,754.0 NS	409,036.7 **
Cubic	1	35,081,377.0 NS	362,046,340.0 NS	51,193,301.0 NS	201,086.7 **
P X L	9	134,440,860.0 NS	85,028,400.0 NS	20,371,282.0 NS	6,506.9 NS
Replications	2	278,532,620.0 NS	74,234,807.0 NS	9,078,633.5 NS	2,286.9 NS
Error	30	81,168,153.0	55,899,302.0	5,877,555.1	3,100.6
Total	47	95,953,989.0	73,180,418.0	10,590,742.0	22,788.4

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 84. Summaries of the analyses of variance of data shown in Table 64.

Sources	df	Soil-legume combinations			
		Oxisol		Spodosol	
		Centrosema	T. repens	Centrosema	T. repens
		Mean squares			
Phosphorus P	3	9,638,303.3 NS	5,814,605.7 NS	64,703.2 **	356.7 NS
Linear	1	5,201,497.0 NS	4,145,859.4 NS	165,668.2 **	610.0 NS
Quadratic	1	22,962,735.0 NS	1,081,185.1 NS	23,112.5 NS	136.1 NS
Cubic	1	750,677.8 NS	12,216,773.0 NS	5,329.0 NS	324.0 NS
Lime L	3	6,910,561.7 NS	18,730,452.0 *	373,999.7 **	287,915.5 **
Linear	1	951,426.3 NS	5,747,724.5 NS	910,940.8 **	100,123.4 **
Quadratic	1	1,247,107.7 NS	1,223,366.0 NS	96,302.1 **	523,336.3 **
Cubic	1	18,533,151.0 NS	49,220,267.0 **	114,756.3 **	240,286.8 **
P X L	9	37,228,178.0 NS	11,338,221.0 NS	82,595.0 **	2,441.8 NS
Replications	2	41,705,364.0 NS	915,080.8 NS	18,430.0 NS	736.0 NS
Error	30	24,601,329.0	5,698,506.3	8,171.6	2,401.5
Total	47	25,662,783.0	7,414,138.5	49,818.6	20,432.1

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 85. Summaries of the analyses of variance of data shown in Table 27.

Sources	df	Plant responses P	 K	 Ca	 Mg
		---------------------	------Mean squares	------	---------------------
Phosphorus P	3	0.00638 **	0.19544 **	0.13422 NS	0.02129 *
Linear	1	0.00667 *	0.26042 **	0.00184 NS	0.03010 *
Quadratic	1	0.01227 **	0.09389 NS	0.39457 NS	0.02683 *
Cubic	1	0.00020 NS	0.23200 *	0.00627 NS	0.00694 NS
Lime L	3	0.01126 **	0.03122 NS	1.28388 **	0.03802 **
Linear	1	0.00210 NS	0.00228 NS	3.80772 **	0.00600 NS
Quadratic	1	0.02385 **	0.00013 NS	0.00152 NS	0.03101 *
Cubic	1	0.00782 *	0.09126 NS	0.04240 NS	0.07704 **
P X L	9	0.00428 **	0.03107 NS	0.09518 NS	0.00808 NS
Replications	2	0.00035 NS	0.04550 NS	0.10890 NS	0.00027 NS
Error	30	0.00112	0.03283	0.10557	0.00619
Total	47	0.00268	0.04331	0.18076	0.00929

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 86. Summaries of the analyses of variance of data shown in Table 28.

Sources	df	Plant responses			
		P	K	Ca	Mg
		---Mean squares---			
Phosphorus P	3	0.17022 **	0.24507 **	0.03696 NS	0.00266 NS
Linear	1	0.03227 NS	0.16170 NS	0.00034 NS	0.00770 NS
Quadratic	1	0.28627 **	0.56711 **	0.06783 NS	0.00003 NS
Cubic	1	0.19214 **	0.00640 NS	0.04271 NS	0.00025 NS
Lime L	3	0.02694 NS	1.18615 **	2.45132 **	0.08261 **
Linear	1	0.04988 NS	2.70938 **	7.28017 **	0.18984 **
Quadratic	1	0.02000 NS	0.21870 *	0.00030 NS	0.05672 **
Cubic	1	0.01094 NS	0.63038 **	0.07350 NS	0.00126 NS
P X L	9	0.01074 NS	0.16288 **	0.12489 **	0.00450 *
Replications	2	0.00566 NS	0.05234 NS	0.01069 NS	0.00265 NS
Error	30	0.00923	0.04556	0.03119	0.00160
Total	47	0.02078	0.15385	0.20310	0.00744

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 87. Summaries of the analyses of variance of data shown in Table 29.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
Phosphorus P	3	1,094.1 **	288.7 NS	12,133.2 **	17,925.9 NS
Linear	1	704.2 NS	682.7 NS	23,625.4 **	5,797.0 NS
Quadratic	1	256.8 NS	29.4 NS	8,385.1 **	47,689.0 NS
Cubic	1	10.0 NS	154.2 NS	4,389.1 **	291.8 NS
Lime L	3	18,385.7 **	1,027.1 *	8,299.3 **	8,308.0 NS
Linear	1	48,621.1 **	630.5 NS	13,575.1 **	6.3 NS
Quadratic	1	5,808.0 **	760.0 NS	6,142.7 **	3,692.5 NS
Cubic	1	728.0 NS	1,690.7 *	5,180.1 **	21,225.2 NS
P X L	9	507.8 NS	426.3 NS	8,664.8 **	22,332.8 NS
Replications	2	118.8 NS	43.5 NS	180.1 NS	34,240.6 NS
Error	30	238.6	237.4	270.9	16,209.3
Total	47	1,497.9	319.0	3,144.0	17,754.4

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 88. Summaries of the analyses of variance of data shown in Table 30.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
Phosphorus P	3	4,929.7 **	6.1 NS	407.8 *	1,632.4 NS
Linear	1	5,581.5 *	12.0 NS	1,190.0 **	1,617.0 NS
Quadratic	1	9,112.5 **	5.0 NS	3.1 NS	125.3 NS
Cubic	1	95.1 NS	1.4 NS	30.2 NS	3,154.7 NS
Lime L	3	117,454.1 **	52.8 **	4,400.2 **	2,480.8 NS
Linear	1	342,997.7 **	126.2 **	9,677.4 **	714.2 NS
Quadratic	1	9,324.2 **	4.1 NS	3,201.3 **	5,504.1 NS
Cubic	1	40.8 NS	28.0 NS	322.0 NS	1,224.0 NS
P X L	9	1,811.5 *	13.9 NS	117.0 NS	5,554.9 **
Replications	2	1,450.9 NS	4.1 NS	11.3 NS	6,408.3 *
Error	30	775.9	13.5	98.0	1,655.0
Total	47	8,715.6	15.2	392.4	2,655.3

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 89. Effects of lime, P, and nutrient combinations* applied to an Oxisol on oven-dry *P. lathyroides* and Siratro herbage and root yields.

CaCO3 applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	g/pot						
	Phaseolus lathyroides herbage						
0	0.2 a**	0.3 a	0.5 a	1.6 bc	1.9 bcd	2.1 cd	1.1
600	0.6 a	0.4 a	3.4 e	1.8 bcd	2.4 d	8.2 g	2.8
1,200	0.3 a	0.3 a	1.4 b	1.6 bc	1.8 bcd	4.5 f	1.7
1,800	0.2 a	0.2 a	0.2 a	1.4 b	0.6 a	0.5 a	0.5
Mean	0.3	0.3	1.4	1.6	1.7	3.8	1.5
	Phaseolus lathyroides roots						
0	0.2 a	0.2 a	0.8 bc	1.5 de	1.2 cd	1.5 de	0.9
600	0.2 a	0.3 ab	1.9 e	1.6 de	1.4 d	2.6 f	1.3
1,200	0.2 a	0.2 a	0.5 ab	1.3 c	1.4 d	2.4 f	1.0
1,800	0.2 a	0.3 ab	0.2 a	0.4 ab	0.6 ab	0.5 ab	0.4
Mean	0.2	0.3	0.9	1.2	1.2	1.8	0.9

Table 89. Continued

$CaCO_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	g/pot						
				Siratro herbage			
0	0.3 a	0.2 a	0.6 ab	1.8 de	2.2 efg	2.9 hij	1.3
600	0.2 a	0.4 a	0.8 abc	3.1 ij	2.4 fgh	4.2 l	2.1
1,200	0.4 a	0.3 a	2.6 ghi	2.0 ef	3.9 l	3.7 kl	2.2
1,800	0.3 a	0.3 a	3.3 jk	1.3 cd	1.8 de	1.1 bc	1.4
Mean	0.3	0.3	1.8	2.0	2.6	3.0	1.7

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within herbage and root groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 98.

Table 90. Effects of lime, P, and nutrient combinations* applied to an Oxisol on Mn, Cu, Zn, and Fe concentrations in oven-dry P. lathyroides herbage.

	P applied, ppm						
	0			50			
CaCO3	Nutrient combinations*			Nutrient combinations			
applied	None	All	All-Fe	None	All	All-Fe	Mean
ppm	ppm						
				Herbage Mn			
0	124 e**	208 jk	216 k	180 h	191 i	239 l	193
600	116 e	170 g	201 j	146 f	164 g	233 l	172
1,200	88 bc	149 f	140 f	104 d	116 e	140 f	123
1,800	69 a	96 cd	141 f	72 a	83 b	115 e	146
Mean	99	156	175	126	139	182	146
				Herbage Cu			
0	9 d	9 d	7 bcd	9 d	9 d	7 bcd	8
600	6 bc	6 bc	5 ab	3 a	7 bcd	5 ab	5
1,200	6 bc	5 ab	7 bcd	6 bc	9 d	3 a	6
1,800	8 cd	7 bcd	8 cd	12 e	9 d	3 a	8
Mean	7	7	7	8	9	5	7

Table 90. Continued

CaCO$_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	ppm						
	Herbage Zn						
0	370 l	250 k	89 gh	90 h	113 i	91 h	167
600	156 j	144 j	69 cde	60 bcd	72 def	82 fgh	97
1,200	75 ef	58 bc	60 bcd	52 ab	61 bcd	77 efg	64
1,800	54 ab	45 a	49 ab	44 a	51 ab	51 ab	49
Mean	164	124	67	62	74	75	94
	Herbage Fe						
0	479 cdefg	666 g	397 bcdef	359 abcde	587 fg	338 abcd	471
600	488 defg	567 efg	329 abcd	233 ab	366 abcde	385 bcdef	395
1,200	215 ab	516 defg	259 ab	214 ab	268 abc	179 ab	275
1,800	212 ab	339 abcde	249 ab	263 abc	250 ab	164 a	246
Mean	349	522	309	267	368	260	346

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 100.

Table 91. Effects of lime, P, and nutrient combinations* applied to an Oxisol on Mn, Cu, Zn, and Fe concentrations in oven-dry Siratro herbage.

	P applied, ppm						
	0			50			
CaCO$_3$ applied	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	ppm						
				Herbage Mn			
0	517 l**	622 m	386 j	338 h	463 k	179 f	418
600	338 h	240 g	148 ef	163 f	160 f	117 de	194
1,200	175 f	150 ef	69 ab	90 bcd	57 a	109 cd	108
1,800	107 cd	82 abc	65 ab	105 cd	51 a	66 ab	79
Mean	284	274	167	174	183	118	200
				Herbage Cu			
0	6 ab	7 abc	7 abc	9 abcde	11 bcde	13 de	9
600	9 abcde	5 a	9 abcde	9 abcde	8 abcd	8 abcd	8
1,200	12 cde	10 abcde	9 abcde	8 abcd	14 e	9 abcde	10
1,800	8 abcd	11 bcde	7 abc	9 abcde	13 de	6 ab	9
Mean	9	8	8	9	12	9	9

Table 91. Continued

CaCO$_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	ppm						
	Herbage Zn						
0	213 l	189 k	195 kl	117 def	124 efg	133 fghi	162
600	163 j	150 ij	147 hij	102 abcd	101 abcd	112 cde	129
1,200	125 efg	139 ghl	114 cdef	90 a	92 ab	111 bcde	112
1,800	94 abc	129 efgh	95 abc	95 abc	102 abcd	109 abcde	104
Mean	149	152	138	101	105	116	127
	Herbage Fe						
0	399 ab	1,248 c	392 ab	355 ab	361 ab	341 a	516
600	414 ab	625 b	293 a	314 a	338 a	305 a	382
1,200	341 a	398 ab	275 a	262 a	468 ab	269 a	336
1,800	301 a	416 ab	236 a	299 a	468 ab	296 a	336
Mean	364	672	299	308	409	303	392

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 109.

Table 92. Effects of lime, P, and nutrient combinations* applied to an Entisol on Mn, Cu, Zn, and Fe concentrations in oven-dry *P. lathyroides* herbage.

CaCO$_3$ applied	P applied, ppm				
	0		50		
	Nutrient combinations*		Nutrient combinations		
	None	All	None	All	Mean
ppm	ppm				
		Herbage Mn			
0	533 ef**	573 f	462 d	522 e	523
600	267 c	263 c	209 b	258 c	249
1,200	82 a	99 a	113 a	90 a	96
1,800	72 a	70 a	81 a	70 a	73
Mean	239	251	216	235	235
		Herbage Cu			
0	16 g	15 fg	7 abc	5 a	11
600	9 bcde	9 bcde	6 ab	7 abc	8
1,200	10 cde	10 cde	7 abc	7 abc	9
1,800	12 ef	11 de	8 abcd	8 abcd	10
Mean	12	11	7	7	9
		Herbage Zn			
0	105 c	185 d	38 a	39 a	92
600	50 b	61 b	38 a	38 a	47
1,200	56 b	55 b	34 a	35 a	45
1,800	50 b	55 b	32 a	37 a	44
Mean	65	89	36	37	57
		Herbage Fe			
0	282 ef	307 f	118 a	238 bcd	236
600	151 a	208 bc	122 a	247 d	182
1,200	149 a	243 cd	131 a	226 bcd	187
1,800	263 de	282 ef	126 a	205 b	219
Mean	211	260	124	229	206

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 105.

Table 93. Effects of lime, P, and nutrient combinations* applied to an Entisol on Mn, Cu, Zn, and Fe concentrations in oven-dry Siratro herbage.

$CaCO_3$ applied	P applied, ppm				
	0		50		
	Nutrient combinations*		Nutrient combinations		
	None	All	None	All	Mean
ppm	ppm				
	Herbage Mn				
0	254 g**	345 h	190 f	264 g	263
600	280 g	252 g	151 e	201 f	221
1,200	173 ef	142 de	104 cd	102 bc	130
1,800	85 abc	53 a	64 ab	46 a	62
Mean	198	198	127	153	169
	Herbage Cu				
0	10 abcd	17 e	6 ab	5 a	10
600	13 cde	11 abcde	8 abc	10 abcd	11
1,200	9 abcd	9 abcd	7 abc	12 bcde	9
1,800	15 de	10 abcd	9 abcd	11 abcde	11
Mean	12	12	8	10	11
	Herbage Zn				
0	142 c	168 d	123 bc	118 abc	138
600	114 ab	122 bc	116 ab	113 ab	116
1,200	113 ab	118 abc	96 a	112 ab	110
1,800	102 ab	106 ab	102 ab	104 ab	104
Mean	118	129	109	112	117
	Herbage Fe				
0	333 ab	422 b	228 a	231 a	304
600	436 b	381 ab	315 ab	318 ab	363
1,200	301 ab	407 ab	320 ab	320 ab	337
1,800	339 ab	413 ab	369 ab	387 ab	377
Mean	352	406	308	314	345

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 111.

Table 94. Effects of lime, P, and nutrient combinations* applied to an Oxisol on P, K, Ca, and Mg concentrations in oven-dry *P. lathyroides* roots.

CaCO$_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	%						
				Root P			
0	0.05 a**	0.07 abc	0.07 abc	0.12 fg	0.11 efg	0.09 cde	0.09
600	0.09 cde	0.06 ab	0.11 efg	0.13 g	0.10 def	0.12 fg	0.10
1,200	0.07 abc	0.08 bcd	0.07 abc	0.13 g	0.10 def	0.10 def	0.09
1,800	0.06 ab	0.07 abc	0.07 abc	0.09 cde	0.08 bcd	0.07 abc	0.07
Mean	0.07	0.07	0.08	0.12	0.10	0.10	0.09
				Root K			
0	0.54 a	0.57 ab	0.76 cd	0.86 def	0.70 bc	0.90 efg	0.72
600	1.04 ghijk	0.71 c	1.11 ijkl	1.06 hijk	0.98 fghi	1.00 fghij	0.98
1,200	0.99 fghi	1.00 fghij	1.25 l	1.21 l	1.16 kl	0.95 fgh	1.09
1,800	0.94 efgh	0.81 cde	0.92 efgh	1.14 jkl	0.99 fghi	0.98 fghi	0.96
Mean	0.88	0.77	1.01	1.07	0.96	0.96	0.94

Table 94. Continued

CaCO$_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	%						
				Root Ca			
0	0.65 abc	0.69 bcd	0.60 ab	0.53 a	0.53 a	0.59 ab	0.60
600	0.94 ghi	0.79 def	0.80 def	0.72 bcde	1.02 hijk	0.75 cde	0.84
1,200	0.99 hij	1.04 ijk	0.90 fg	1.09 jk	1.04 ijk	0.84 efg	0.98
1,800	1.10 jk	1.14 k	1.08 jk	1.14 k	1.11 jk	1.07 ijk	1.11
Mean	0.92	0.92	0.85	0.87	0.93	0.81	0.88
				Root Mg			
0	0.21 a	0.24 ab	0.29 c	0.20 a	0.21 a	0.32 cd	0.25
600	0.35 de	0.28 bc	0.41 fg	0.32 cd	0.44 g	0.44 g	0.37
1,200	0.29 c	0.30 c	0.41 fg	0.42 g	0.45 g	0.36 de	0.37
1,800	0.29 c	0.28 bc	0.37 ef	0.45 g	0.42 g	0.41 fg	0.37
Mean	0.29	0.28	0.37	0.35	0.38	0.38	0.34

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 101.

Table 95. Effects of lime, P, and nutrient combinations* applied to an Entisol on P, K, Ca, and Mg concentrations in oven-dry P. lathyroides roots.

CaCO$_3$ applied	P applied, ppm				
	0		50		
	Nutrient combinations*		Nutrient combinations		
	None	All	None	All	Mean
ppm	%				
			Root P		
0	0.11 ab**	0.13 b	0.09 a	0.10 a	0.11
600	0.09 a	0.13 b	0.09 a	0.10 a	0.10
1,200	0.10 a	0.11 ab	0.10 a	0.10 a	0.10
1,800	0.10 a	0.11 ab	0.11 ab	0.10 a	0.11
Mean	0.10	0.12	0.10	0.10	0.11
			Root K		
0	0.68 bcd	0.71 de	1.00 h	0.69 cd	0.77
600	0.94 gh	0.48 a	0.87 fgh	0.68 bcd	0.74
1,200	0.83 defg	0.53 ab	0.86 efgh	0.78 def	0.75
1,800	0.85 efgh	0.54 abc	0.90 fgh	0.83 defg	0.78
Mean	0.83	0.57	0.91	0.75	0.77
			Root Ca		
0	1.12 a	1.04 a	1.20 ab	1.13 a	1.12
600	1.19 ab	1.50 cd	1.40 bcd	1.21 ab	1.33
1,200	1.46 cd	1.48 cd	1.59 d	1.34 bc	1.47
1,800	1.90 e	2.28 f	1.52 cd	1.48 cd	1.80
Mean	1.42	1.58	1.43	1.29	1.43
			Root Mg		
0	0.51 abcd	0.53 bcde	0.53 bcde	0.44 a	0.50
600	0.53 bcde	0.47 abc	0.51 abcd	0.45 ab	0.49
1,200	0.63 fg	0.70 g	0.60 ef	0.50 abcd	0.61
1,800	0.58 def	0.54 cde	0.50 abcd	0.51 abcd	0.53
Mean	0.56	0.56	0.54	0.48	0.54

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 106.

Table 96. Effects of lime, P, and nutrient combinations* applied to an Oxisol on Mn, Cu, Zn, and Fe concentrations in oven-dry P. lathyroides roots.

CaCO$_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			Nutrient combinations			
	None	All	All-Fe	None	All	All-Fe	Mean
ppm	%						
				Root Mn			
0	219 f**	216 f	256 g	132 c	266 g	362 h	242
600	173 d	158 d	197 ef	109 ab	179 de	158 d	162
1,200	128 bc	102 a	129 bc	105 a	133 c	119 abc	119
1,800	108 ab	115 abc	110 abc	105 a	113 abc	105 a	109
Mean	157	148	173	113	173	186	158
				Root Cu			
0	26 c	48 d	21 abc	15 abc	24 bc	18 abc	25
600	18 abc	23 abc	12 ab	10 a	18 abc	11 ab	15
1,200	21 abc	24 bc	11 ab	16 abc	16 abc	10 a	16
1,800	22 abc	16 abc	11 ab	17 abc	11 ab	10 a	15
Mean	22	28	14	15	17	12	18

Table 96. Continued

$CaCO_3$ applied	P applied, ppm						
	0			50			
	Nutrient combinations*			None	All	All-Fe	Mean
ppm	ppm						
			Root Zn				
0	114 gh	153 i	68 de	42 abc	51 bcde	53 bcde	80
600	92 fg	136 hi	51 bcde	35 a	51 bcde	45 abc	68
1,200	72 ef	133 hi	49 bcd	41 abc	36 ab	38 abc	62
1,800	60 cde	102 g	51 bcde	36 ab	37 ab	40 abc	54
Mean	85	131	55	39	44	44	66
			Root Fe				
0	3,914 cdefg	4,397 defg	2,974 abcde	4,639 efg	1,776 a	4,413 defg	3,686
600	5,667 gh	3,815 bcdefg	3,341 abcdef	3,220 abcdef	3,286 abcdef	4,583 efg	3,985
1,200	4,902 fg	6,431 h	1,631 a	3,407 abcdef	2,438 abc	2,246 abc	3,509
1,800	4,327 defg	5,413 gh	3,216 abcdef	1,993 ab	2,526 abcd	2,296 abc	3,295
Mean	4,703	5,014	2,791	3,315	2,507	3,385	3,619

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 102.

Table 97. Effects of lime, P, and nutrient combinations* applied to an Entisol on Mn, Cu, Zn, and Fe concentrations in oven-dry *P. lathyroides* roots.

$CaCO_3$ applied	P applied, ppm				
	0		50		
	Nutrient combinations*		Nutrient combinations		
	None	All	None	All	Mean
ppm	ppm				
			Root Mn		
0	286 g**	375 h	208 ef	223 f	273
600	191 ef	215 f	135 bcd	227 f	192
1,200	125 bc	172 de	127 bc	145 cd	142
1,800	83 a	84 a	101 ab	82 a	88
Mean	171	212	143	169	174
			Root Cu		
0	37 ab	30 ab	17 a	24 a	27
600	34 ab	46 b	22 a	29 ab	33
1,200	36 ab	45 b	26 ab	33 ab	35
1,800	35 ab	24 a	29 ab	32 ab	30
Mean	36	36	24	30	32
			Root Zn		
0	166 e	157 e	35 a	38 a	99
600	113 c	137 d	37 a	37 a	81
1,200	68 b	100 c	40 a	42 a	63
1,800	63 b	60 b	41 a	40 a	51
Mean	103	114	38	39	74
			Root Fe		
0	17,411 a	24,774 a	12,664 a	12,149 a	16,750
600	15,657 a	14,429 a	5,597 a	14,878 a	12,640
1,200	30,645 a	16,932 a	16,500 a	13,592 a	19,417
1,800	5,470 a	25,578 a	17,676 a	7,895 a	14,155
Mean	17,296	20,428	13,109	12,129	15,741

* Nutrients were applied according to specifications shown in Table 6.

** Numbers within element groups not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 107.

Table 98. Summaries of the analyses of variance of data shown in Table 89.

Sources	df	Phaseolus lathyroides Herbage	Phaseolus lathyroides Roots	Siratro Herbage
		--------------Mean squares----------------		
Phosphorus P	1	69.871 **	21.282 **	73.500 **
Nutrient combinations Nc	2	28.656 **	3.762 **	12.829 **
P X Nc	2	3.342 **	0.022 NS	2.532 **
Lime L	3	22.378 **	4.045 **	3.971 **
Linear	1	10.238 **	5.125 **	0.085 NS
Quadratic	1	47.461 **	6.720 **	10.800 **
Cubic	1	9.436 **	0.290 NS	1.027 **
P X L	3	4.296 **	1.335 **	7.839 **
Nc X L	6	12.227 **	0.965 **	0.945 **
P X Nc X L	6	2.029 **	0.236 *	3.386 **
Replications	3	0.121 NS	0.042 NS	0.066 NS
Error	69	0.152	0.081	0.111
Total	95	3.266	0.610	1.826

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 99. Summaries of the analyses of variance of data shown in Table 32.

Sources	df	Plant responses P	 K	 Ca	 Mg
		----------------------------	-Mean squares-	----------------------------	
Phosphorus P	1	0.16500 **	0.07205 **	0.13350 **	0.01475 **
Nutrient combinations Nc	2	0.00538 **	0.07400 **	1.38548 **	0.00180 NS
P X Nc	2	0.00363 **	0.06674 **	0.22633 **	0.00801 **
Lime L	3	0.00153 **	0.83050 **	5.53660 **	0.00710 *
Linear	1	0.00280 **	2.48688 **	15.20832 **	0.00238 NS
Quadratic	1	0.00082 *	0.00023 NS	1.39684 **	0.00003 NS
Cubic	1	0.00096 **	0.00438 NS	0.00290 NS	0.01888 **
P X L	3	0.00327 **	0.04407 **	0.26378 **	0.01251 **
Nc X L	6	0.00160 **	0.00795 NS	0.10149 **	0.01023 **
P X Nc X L	6	0.00046 *	0.01569 *	0.06131 **	0.00814 **
Replications	3	0.00006 NS	0.00009 NS	0.01050 NS	0.00151 NS
Error	69	0.00015	0.00626	0.01943	0.00106
Total	95	0.00232	0.03738	0.24322	0.00296

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 100. Summaries of the analyses of variance of data shown in Table 90.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
Phosphorus P	1	742.6 **	0.2 NS	54,626.0 **	441,866.3 **
Nutrient combinations Nc	2	34,625.8 **	28.3 **	14,459.6 **	476,210.7 **
P X Nc	2	3,731.3 **	34.3 **	24,640.8 **	127,737.6 **
Lime L	3	47,180.7 **	45.7 **	66,625.1 **	477,360.3 **
Linear	1	138,482.1 **	0.3 NS	181,274.1 **	1,331,729.4 **
Quadratic	1	213.0 *	130.7 **	18,205.0 **	97,601.3 *
Cubic	1	2,847.0 **	6.1 *	396.0 *	2,750.4 NS
P X L	3	1,670.3 **	0.9 NS	25,270.9 **	44,444.9 *
Nc X L	6	1,045.6 **	9.5 **	9,676.1 **	93,848.5 **
P X Nc X L	6	474.4 **	17.2 **	7,654.6 **	43,597.4 *
Replications	3	16.4 **	0.4 **	39.0 NS	14,121.3 NS
Error	69	43.1	1.1	57.0	15,805.9
Total	95	2,485.8	5.3	5,437.3	54,450.8

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 101. Summaries of the analyses of variance of data shown in Table 94.

Sources	df	Plant responses			
		P	K	Ca	Mg
		Mean squares			
Phosphorus P	1	0.02220 **	0.27628 **	0.01307 NS	0.08461 **
Nutrient combinations Nc	2	0.00045 NS	0.13925 **	0.06924 **	0.03123 **
P X Nc	2	0.00213 **	0.15208 **	0.00719 NS	0.01821 **
Lime L	3	0.00394 **	0.58635 **	1.14388 **	0.09441 **
Linear	1	0.00271 **	0.83250 **	3.34334 **	0.16465 **
Quadratic	1	0.00770 **	0.91846 **	0.08284 **	0.09818 **
Cubic	1	0.00140 *	0.00808 NS	0.00547 NS	0.20410 **
P X L	3	0.00086 *	0.03590 **	0.01450 *	0.01474 **
Nc X L	6	0.00110 **	0.03224 **	0.01567 *	0.00430 **
P X Nc X L	6	0.00025 NS	0.03898 **	0.04012 **	0.01096 **
Replications	3	0.00016 NS	0.00655 NS	0.00302 NS	0.00126 NS
Error	69	0.00021	0.00678	0.00608	0.00065
Total	95	0.00068	0.03832	0.04637	0.00686

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 102. Summaries of the analyses of variance of data shown in Table 96.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
Phosphorus P	1	117.0 NS	988.2 **	56,018.3 **	29,727,117.0 **
Nutrient combinations Nc	2	16,114.1 **	733.0 **	12,138.8 **	7,036,230.5 **
P X Nc	2	10,974.4 **	165.0 NS	11,787.5 **	19,826,707.0 **
Lime L	3	87,347.9 **	569.0 **	2,814.6 **	2,021,987.4 NS
Linear	1	233,112.7 **	1,122.4 **	8,275.1 **	2,967,150.3 NS
Quadratic	1	28,912.0 **	3,603.8 **	133.0 NS	1,742,317.6 NS
Cubic	1	19.2 NS	2,241.3 **	35.8 NS	1,356,494.4 NS
P X L	3	2,572.7 **	103.0 NS	903.4 **	4,494,998.6 *
Nc X L	6	7,641.7 **	163.8 *	211.1 NS	5,020,713.3 *
P X Nc X L	6	4,689.2 **	41.0 NS	333.5 NS	2,944,333.6 NS
Replications	3	591.4 *	124.9 NS	26.6 NS	894,004.1 NS
Error	69	199.0	58.7	191.2	1,233,725.1
Total	95	4,353.1	110.0	138.5	2,511,613.4

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 103. Summaries of the analyses of variance of data shown in Table 31.

		Phaseolus lathyroides		Siratro
Sources	df	Herbage	Roots	Herbage
		Mean squares		
Phosphorus P	1	6.760 **	6.002 **	7.089 **
Nutrient combinations Nc	1	0.006 NS	0.016 NS	2.600 **
P X Nc	1	0.022 NS	0.122 *	7.223 **
Lime L	3	0.220 **	0.336 **	11.490 **
Linear	1	0.364 **	0.903 **	29.222 **
Quadratic	1	0.075 NS	0.076 NS	4.358 **
Cubic	1	0.220 **	0.028 NS	0.892 NS
P X L	3	0.118 *	0.212 **	7.905 **
Nc X L	3	0.120 *	0.016 NS	0.161 NS
P X Nc X L	3	0.139 *	0.020 NS	1.021 *
Replications	3	0.044 NS	0.096 *	0.195 NS
Error	45	0.028	0.028	0.258
Total	63	0.158	0.150	1.442

* Significant F test at the 5% level.

** Sifnificant F test at the 1% level.

Table 104. Summaries of the analyses of variance of data shown in Table 34.

Sources	df	Plant responses			
		P	K	Ca	Mg
		Mean squares			
Phosphorus P	1	0.05006 **	0.97022 **	0.65408 **	0.95550 **
Nutrient combinations Nc	1	0.00035 NS	0.23522 **	0.01531 NS	0.03331 **
P X Nc	1	0.00131 **	0.01822 NS	0.35254 **	0.01626 **
Lime L	3	0.00009 NS	0.01857 NS	1.71257 **	0.08696 **
Linear	1	0.00009 NS	0.03362 NS	5.10808 **	0.14535 **
Quadratic	1	0.00019 NS	0.00160 NS	0.00701 NS	0.11056 **
Cubic	1	0.00001 NS	0.02048 NS	0.02261 NS	0.00496 NS
P X L	3	0.00081 **	0.00740 NS	0.13117 **	0.02607 **
Nc X L	3	0.00029 NS	0.01088 NS	0.26193 **	0.00382 NS
P X Nc X L	3	0.00029 NS	0.00358 NS	0.06824 **	0.00172 NS
Replications	3	0.00001 NS	0.04048 NS	0.01298 NS	0.00138 NS
Error	45	0.00012	0.02720	0.01152	0.00190
Total	63	0.00098	0.04271	0.12858	0.02302

** Significant F test at the 1% level.

Table 105. Summaries of the analyses of variance of data shown in Table 92.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		------Mean squares------			
Phosphorus P	1	6,064.5 *	361.0 **	26,609.8 **	51,415.6 **
Nutrient combinations Nc	1	3,890.6 NS	0.6 NS	2,665.1 **	88,655.1 **
P X Nc	1	129.4 NS	0.6 NS	1,969.1 **	10,609.0 **
Lime L	3	684,658.0 **	29.0 **	8,650.8 **	12,344.0 **
Linear	1	1,802,250.7 **	5.5 NS	16,921.6 **	2,820.3 **
Quadratic	1	251,627.6 **	72.2 **	7,547.3 **	33,124.0 **
Cubic	1	95.7 NS	9.1 NS	1,483.5 **	1,087.8 NS
P X L	3	4,571.4 **	41.0 **	7,602.1 **	14,033.6 **
Nc X L	3	2,777.7 *	5.1 NS	1,418.7 **	1,897.1 *
P X Nc X L	3	1,631.8 NS	0.3 NS	1,454.1 **	1,170.5 NS
Replications	3	363.3 NS	8.3 NS	65.1 NS	419.5 NS
Error	45	972.7	3.0	39.3	489.4
Total	63	33,902.6	11.9	1,437.8	4,163.4

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 106. Summaries of the analyses of variance of data shown in Table 95.

Sources	df	Plant responses			
		P	K	Ca	Mg
		Mean squares			
Phosphorus P	1	0.00263 **	0.27826 **	0.29839 **	0.04622 **
Nutrient combinations Nc	1	0.00170 **	0.70141 **	0.00238 NS	0.01690 **
P X Nc	1	0.00170 **	0.04101 *	0.35551 **	0.01210 *
Lime L	3	0.00009 NS	0.00482 NS	1.28109 **	0.04239 **
Linear	1	0.00001 NS	0.00091 NS	3.73896 **	0.03403 **
Quadratic	1	0.00026 NS	0.01322 NS	0.06313 NS	0.01501 *
Cubic	1	0.00002 NS	0.00032 NS	0.04118 NS	0.07812 **
P X L	3	0.00030 NS	0.00866 NS	0.37942 **	0.00771 NS
Nc X L	3	0.00063 NS	0.02616 NS	0.06696 *	0.00176 NS
P X Nc X L	3	0.00016 NS	0.08802 **	0.05039 *	0.00940 **
Replications	3	0.00009 NS	0.01237 NS	0.05554 *	0.00069 NS
Error	45	0.00014	0.00801	0.01631	0.00220
Total	63	0.00025	0.02859	0.10937	0.00571

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 107. Summaries of the analyses of variance of data shown in Table 97.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
Phosphorus P	1	20,022.2 **	1,396.9 **	76,312.1 **	62,362,576.0 NS
Nutrient combinations Nc	1	17,689.0 **	192.5 NS	552.2 **	18,513,658.0 NS
P X Nc	1	715.6 NS	112.9 NS	400.0 **	67,687,643.0 NS
Lime L	3	99,778.7 **	206.4 NS	7,243.8 **	142,202,350.0 NS
Linear	1	295,609.6 **	111.6 NS	21,516.8 **	812,851.2 NS
Quadratic	1	2,704.0 *	500.6 NS	175.6 NS	5,313,025.0 NS
Cubic	1	1,022.4 NS	6.9 NS	39.2 NS	4,204,811.8 NS
P X L	3	11,904.8 **	211.9 NS	8,588.6 **	35,417,564.0 NS
Nc X L	3	3,688.6 **	169.1 NS	399.9 **	15,871,522.0 NS
P X Nc X L	3	3,515.1 **	102.8 NS	409.4 **	37,165,103.0 NS
Replications	3	1,225.6 NS	4.8 NS	63.9 NS	12,041,424.0 NS
Error	45	649.1	135.8	70.9	71,544,245.0
Total	63	6,793.2	157.1	2,072.6	96,657,156.0

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 108. Summaries of the analyses of variance of data shown in Table 33.

Sources	df	Plant responses			
		P	K	Ca	Mg
		Mean squares			
Phosphorus P	1	0.00070 NS	2.78802 **	4.85550 **	3.09242 **
Nutrient combinations Nc	2	0.00507 **	0.92784 **	2.13320 **	0.69054 **
P X Nc	2	0.00135 *	1.07728 **	0.07072 *	0.23693 **
Lime L	3	0.00904 **	0.48294 **	2.12297 **	0.13455 **
Linear	1	0.02107 **	0.19521 *	6.35950 **	0.36908 **
Quadratic	1	0.00602 **	1.25127 **	0.00940 NS	0.01148 NS
Cubic	1	0.00004 NS	0.00234 NS	0.00001 NS	0.02310 NS
P X L	3	0.00651 **	0.40977 **	0.13437 **	0.03948 **
Nc X L	6	0.00871 **	0.05900 NS	0.12897 **	0.04811 **
P X Nc X L	6	0.00315 **	0.60576 **	0.20038 **	0.04189 **
Replications	3	0.00006 NS	0.01295 NS	0.02569 NS	0.01528 NS
Error	69	0.00039	0.04096	0.02005	0.00829
Total	95	0.00167	0.17189	0.20491	0.06976

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 109. Summaries of the analyses of variance of data shown in Table 91.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
Phosphorus P	1	166,666.7 **	36.3 *	35,998.7 **	265,125.3 **
Nutrient combinations Nc	2	79,130.3 **	15.3 NS	84.3 NS	535,383.0 **
P X Nc	2	7,750.2 **	20.9 NS	1,820.5 **	156,668.2 **
Lime L	3	562,652.1 **	17.5 NS	15,745.8 **	175,032.6 **
Linear	1	1,453,100.0 **	9.4 NS	43,377.0 **	413,424.1 **
Quadratic	1	227,176.0 **	1.8 NS	3,812.7 **	109,552.6 **
Cubic	1	7,680.0 **	41.4 NS	47.5 NS	2,121.0 NS
P X L	3	32,930.7 **	25.9 NS	5,344.9 **	159,568.8 **
Nc X L	6	30,663.3 **	28.0 NS	396.0 *	53,838.8 NS
P X Nc X L	6	5,303.9 **	8.2 NS	400.0 *	124,331.1 NS
Replications	3	832.1 NS	7.0 NS	237.2 NS	11,058.9 NS
Error	69	470.5	8.8	140.4	26,517.2
Total	95	25,030.9	11.4	1,244.8	58,788.6

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 110. Summaries of the analyses of variance of data shown in Table 35.

Sources	df	Plant responses			
		P	K	Ca	Mg
		Mean squares			
Phosphorus P	1	0.01594 **	0.35254 **	0.68269 **	0.01156 NS
Nutrient combinations Nc	1	0.00019 NS	0.00439 NS	0.57950 **	0.03901 **
P X Nc	1	0.00289 **	0.00045 NS	0.01925 NS	0.02641 **
Lime L	3	0.00537 **	0.10293 *	1.02648 **	0.00198 NS
Linear	1	0.00892 **	0.28860 **	2.61907 **	0.00231 NS
Quadratic	1	0.00701 **	0.00114 NS	0.44723 **	0.00122 NS
Cubic	1	0.00016 NS	0.01906 NS	0.01313 NS	0.00242 NS
P X L	3	0.00134 **	0.08343 NS	0.16934 **	0.03002 **
Nc X L	3	0.00026 NS	0.03846 NS	0.02869 NS	0.00632 NS
P X Nc X L	3	0.00120 NS	0.01794 NS	0.00203 NS	0.00348 NS
Replications	3	0.00008 NS	0.05184 NS	0.01173 NS	0.00176 NS
Error	45	0.00018	0.02929	0.01830	0.00547
Total	63	0.00082	0.04062	0.09237	0.00720

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 111. Summaries of the analyses of variance of data shown in Table 93.

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		---Mean squares---			
Phosphorus P	1	53,245.6 **	162.6 **	2,450.2 **	78,190.1 **
Nutrient combinations Nc	1	2,835.5 **	16.0 NS	702.2 *	15,970.6 NS
P X Nc	1	2,704.0 **	16.0 NS	256.0 NS	7,590.7 NS
Lime L	3	130,852.1 **	12.7 NS	3,552.7 **	18,401.3 NS
Linear	1	385,864.2 **	7.8 NS	9,504.8 **	34,010.6 NS
Quadratic	1	2,730.1 *	5.1 NS	961.0 *	2,081.6 NS
Cubic	1	3,962.1 *	25.3 NS	192.2 NS	19,112.0 NS
P X L	3	4,329.3 **	59.1 **	932.7 **	18,899.3 NS
Nc X L	3	9,610.8 **	17.4 NS	70.1 NS	5,991.1 NS
P X Nc X L	3	1,539.3 NS	54.1 **	296.7 NS	5,069.7 NS
Replications	3	694.3 NS	2.2 NS	50.3 NS	2,515.1 NS
Error	45	560.2	12.6	211.2	11,765.5
Total	63	8,334.5	19.0	438.4	12,441.7

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 112. Effects of lime and applied P on exchangeable Ca from an Oxisol, Spodosol, and Entisol.

P applied	CaCO$_3$ applied, ppm			
	0	600	1,200	1,800
ppm	Ca, meq/100 g			
		Oxisol		
0	3.15	4.85	5.75	5.85
50	3.35	5.05	5.55	5.75
Mean	3.25	4.95	5.65	5.80
		Spodosol		
0	0.95	1.49	1.85	1.95
75	1.03	1.60	1.83	1.99
Mean	0.99	1.55	1.84	1.97
		Entisol		
0	6.15	7.55	7.00	7.10
50	6.45	7.75	7.68	7.85
Mean	6.30	7.65	7.34	7.48

Table 113. Effects of lime and applied P on electrical conductivities of saturated extracts from an Oxisol and Entisol, liming experiment 2.

P applied ppm	CaCO$_3$ applied, ppm 0	600	1,200	1,800
	Conductivities, mmhos/cm			
		Oxisol		
0	1.3	0.8	1.1	1.0
50	0.7	0.5	0.9	0.7
Mean	1.0	0.7	1.0	0.9
		Entisol		
0	5.5	5.8	5.9	6.4
50	4.8	6.0	6.2	6.0
Mean	5.2	5.9	6.1	6.2

Table 114. Phosphorus extracted by Bray's reagent from four soils after 72-hour incubation with different rates of P.

P applied	Oxisol		Unlimed soils		
	Unlimed	Limed	Spodosol	Entisol	Inceptisol
ppm	P, ppm				
0	13.3 a*	20.0 a	14.0	52.0	14.1
50	29.4 a	30.8 a	49.4	70.1	21.2
100	38.5 a	39.9 a	91.0	82.3	27.9
150	56.0 a	52.5 a	127.8	87.8	34.8
200	67.9 a	61.6 a	163.8	99.9	42.4
300	81.2 a	76.7 a	217.7	110.0	70.0
500	158.8 b	134.4 a	350.0	147.0	119.1

* Numbers within P rates for the Oxisol not followed by a common letter are significantly different at the 5% level.

Table 115. Effects of P applied to an Inceptisol, Oxisol, and Entisol on oven-dry yields and P, K, Ca, and Mg concentrations in P. lathyroides roots under greenhouse conditions.

P applied	Root yields	Nutrient concentrations			
		P	K	Ca	Mg
ppm	g/pot	%			
		Inceptisol			
0	0.5 a*	0.16 a	1.61 b	0.30 b	1.16 a
50	0.9 b	0.12 a	1.43 a	0.19 a	0.88 a
100	0.8 b	0.15 a	1.85 c	0.20 a	0.92 a
200	0.5 a	0.29 b	2.60 d	0.23 a	1.23 a
		Oxisol			
0	0.2 a	0.06 a	0.85 a	0.54 a	0.31 a
50	0.6 b	0.08 a	1.08 b	0.48 a	0.34 ab
100	0.7 b	0.08 a	1.28 c	0.54 a	0.42 a
200	0.6 b	0.12 b	1.76 d	0.47 a	0.40 bc
		Entisol			
0	0.2 a	0.06 a	1.03 a	1.04 b	0.37 a
50	0.3 a	0.12 b	2.20 b	0.96 b	0.53 b
100	0.4 ab	0.16 c	2.98 c	0.67 a	0.54 b
200	0.6 b	0.28 d	3.07 c	0.68 a	0.44 ab

* Numbers within vertical columns, within soil groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 122.

Table 116. Effects of P applied to an Inceptisol, Oxisol, and Entisol on Mn, Cu, Zn, and Fe concentrations in oven-dry P. lathyroides roots under greenhouse conditions.

P applied	Nutrient concentrations			
	Mn	Cu	Zn	Fe
ppm	ppm			
		Inceptisol		
0	112 b*	7 a	92 b	3,162 a
50	78 a	5 a	40 a	2,502 a
100	56 a	4 a	30 a	1,417 a
200	82 a	4 a	32 a	1,954 a
		Oxisol		
0	593 c	19 a	166 b	5,663 a
50	282 b	12 a	49 a	2,811 a
100	166 a	11 a	44 a	6,642 b
200	140 a	12 a	35 a	3,471 a
		Entisol		
0	162 ab	16 b	83 c	445 a
50	182 b	15 ab	60 b	496 a
100	141 a	11 ab	58 b	335 a
200	160 ab	10 a	39 a	421 a

* Numbers within vertical columns, within soil groups, not followed by a common letter are significantly different at the 5% level. Summaries of the analyses of variance are shown in Table 123.

Table 117. Effect of P applied to an Inceptisol on oven-dry *Centrosema* and Siratro herbage yields from the second harvest at Izabal, Guatemala.

P applied	Legumes	
	Centrosema	Siratro
kg/ha	kg/6 m^2	
0	8.3 a*	9.4 ab
150	9.3 ab	10.4 b
300	9.4 ab	10.7 b

* Numbers not followed by a common letter are not significantly different at the 5% level. Summary of the analysis of variance is shown in Table 118.

Table 118. Summary of the analysis of variance of data shown in Table 117.

Sources	df	Mean squares
Legumes Le	1	8.167 *
Phosphorus P	2	3.345 NS
Linear	1	5.641 NS
Quadratic	1	1.050 NS
Le X P	2	0.040 NS
Error	18	1.170
Total	23	1.565

* Significant F test at the 5% level.

Table 119. Phosphorus extracted by Mehlich's reagent (0.05N HCl and 0.025N H_2SO_4) from an Oxisol and Inceptisol at different rates of P applied under field conditions.

Soil depth	P applied, kg/ha		
	0	100	200
cm	P extracted, ppm		
	Oxisol		
0-8	4.3	13.3	28.7
	Inceptisol		
0-8	12.5	21.3	33.6
6-15	2.4	4.7	7.3

Table 120. Summaries of the analyses of variance shown in Table 37.

Sources	df	Plant responses				
		Yield	P	K	Ca	Mg
		Mean squares				
				Inceptisol		
Phosphorus	3	3.456 **	0.03872 **	4.72970 **	0.04037 **	0.38512 **
Linear	1	6.710 **	0.11315 **	10.36864 **	0.00228 NS	1.08680 **
Quadratic	1	3.632 **	0.00186 **	1.96146 **	0.11619 **	0.05036 **
Cubic	1	0.025 NS	0.00114 **	1.85900 **	0.00266 NS	0.01820 NS
Error	12	0.064	0.00009	0.03978	0.00904	0.00619
Total	15	0.742	0.00781	0.97777	0.01531	0.08198
				Oxisol		
Phosphorus	3	3.631 **	0.00994 **	2.45599 **	0.61134 **	0.00477 NS
Linear	1	10.287 **	0.02944 **	7.32572 **	0.40932 **	0.00825 *
Quadratic	1	0.215 NS	0.00039 NS	0.03898 NS	1.33902 **	0.00592 NS
Cubic	1	0.390 *	0.00000 NS	0.00327 NS	0.08568 NS	0.00014 NS
Error	12	0.058	0.00041	0.01548	0.05386	0.00138
Total	15	0.773	0.00232	0.50358	0.16536	0.00206

Table 120. Continued

Sources	df	Plant responses				
		Yield	P	K	Ca	Mg
		-----------------------------Mean squares-----------------------------				
				Entisol		
Phosphorus	3	4.145 **	0.04277 **	4.83142 **	0.02357 NS	0.00872 NS
Linear	1	11.543 **	0.12811 **	11.57188 **	0.05945 NS	0.00014 NS
Quadratic	1	0.453 **	0.00020 NS	2.90194 **	0.00951 NS	0.01470 NS
Cubic	1	0.439 **	0.00001 NS	0.02045 NS	0.00176 NS	0.01130 NS
Error	12	0.040	0.00051	0.02081	0.02830	0.00864
Total	15	0.861	0.00896	0.98293	0.02735	0.00865

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 121. Summaries of the analyses of variance of data shown in Table 38.

Sources	df	Mn	Cu	Zn	Fe
		Plant responses			
		-Mean squares-			
			Inceptisol		
Phosphorus	3	3,845.1 **	4.2 NS	149.4 NS	2,013.1 NS
Linear	1	11,457.3 **	0.0 NS	307.5 *	2,204.1 NS
Quadratic	1	18.2 NS	12.3 *	110.6 NS	3,236.6 NS
Cubic	1	59.6 NS	0.4 NS	30.0 NS	600.4 NS
Error	12	181.4	1.8	61.4	2,703.7
Total	15	914.1	2.3	79.0	2,565.7
			Oxisol		
Phosphorus	3	348,725.2 **	3.7 *	110.7 NS	8,933.7 *
Linear	1	696,963.4 **	6.2 *	131.1 NS	20,752.3 **
Quadratic	1	344,571.0 **	4.4 *	177.8 *	6,015.6 NS
Cubic	1	4,641.0 NS	0.6 NS	23.2 NS	3,327.5 NS
Error	12	1,560.5	0.9	35.2	1,826.2
Total	15	70,993.4	1.4	50.3	3,247.7

Table 121. Continued

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		Mean squares			
			Entisol		
Phosphorus	3	14,184.2 **	12.4 **	331.0 **	3,104.2 NS
Linear	1	33,790.2 **	2.6 NS	536.2 **	1,075.3 NS
Quadratic	1	7,518.0 **	30.5 **	142.2 **	6,513.0 NS
Cubic	1	1,244.5 NS	4.2 NS	314.5 **	1,724.2 NS
Error	12	641.6	1.4	12.3	1,673.5
Total	15	3,350.1	3.6	76.0	1,959.7

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 122. Summaries of the analyses of variance of data shown in Table 115.

Sources	df	Plant responses				
		Yield	P	K	Ca	Mg
		---Mean squares---				
		Inceptisol				
Phosphorus	3	0.172 **	0.02341 **	1.05946 **	0.01024 **	0.07898 NS
Linear	1	0.007 NS	0.04847 **	2.68136 **	0.00469 NS	0.01672 NS
Quadratic	1	0.426 **	0.02116 *	0.36917 **	0.02000 **	0.21208 **
Cubic	1	0.082 *	0.00059 NS	0.12784 **	0.00604 NS	0.00812 NS
Error	12	0.011	0.00232	0.00213	0.00142	0.04697
Total	15	0.043	0.00654	0.21359	0.00318	0.05337
		Oxisol				
Phosphorus	3	0.202 **	0.00274 **	0.60137 **	0.00570 NS	0.01096 *
Linear	1	0.175 *	0.00788 **	1.80238 **	0.00578 NS	0.02188 *
Quadratic	1	0.426 **	0.00007 NS	0.00053 NS	0.00031 NS	0.00716 NS
Cubic	1	0.006 NS	0.00028 NS	0.00121 NS	0.01100 NS	0.00384 NS
Error	12	0.020	0.00020	0.00558	0.00312	0.00241
Total	15	0.056	0.00070	0.12474	0.00363	0.00412

Table 122. Continued

Sources	df	Plant responses				
		Yield	P	K	Ca	Mg
		---Mean squares---				
		Entisol				
Phosphorus	3	0.100 **	0.03272 **	3.54566 **	0.14871 **	0.02522 *
Linear	1	0.297 **	0.09778 **	8.01368 NS	0.33272 **	0.00330 NS
Quadratic	1	0.005 NS	0.00022 NS	2.62083 **	0.05883 *	0.06796 **
Cubic	1	0.000 NS	0.00014 NS	0.00246 NS	0.05457 *	0.00439 NS
Error	12	0.011	0.00048	0.00443	0.00767	0.00545
Total	15	0.029	0.00693	0.71267	0.03588	0.00941

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 123. Summaries of the analyses of variance of data shown in Table 116.

		Plant responses			
Sources	df	Mn	Cu	Zn	Fe
		-----------------------------Mean squares	-----------------------------	-----------------------------	-----------------------------
			Inceptisol		
Phosphorus	3	2,140.1 **	8.7 NS	3,363.6 **	2,235,383.7 NS
Linear	1	1,436.8 NS	19.7 *	5,512.6 **	3,232,280.4 NS
Quadratic	1	4,937.6 **	6.4 NS	4,171.4 **	2,896,045.7 NS
Cubic	1	45.8 NS	0.1 NS	406.6 *	577,825.1 NS
Error	12	337.4	2.6	70.9	1,085,129.8
Total	15	698.0	3.8	729.5	1,315,180.6
			Oxisol		
Phosphorus	3	173,153.8 **	49.7 NS	15,314.1 **	13,021,881.0 NS
Linear	1	365,160.7 **	74.3 NS	25,555.5 **	2,971,551.5 NS
Quadratic	1	149,049.0 **	67.6 NS	16,354.3 **	1,417,536.5 NS
Cubic	1	5,250.9 NS	7.1 NS	4,032.3 **	34,676,556.0 *
Error	12	3,552.7	22.9	91.1	4,140,783.0
Total	15	37,472.9	28.3	3,135.7	5,917,003.0

Table 123. Continued

Sources	df	Mn	Cu	Zn	Fe
		Plant responses			
		---Mean squares---			
			Entisol		
Phosphorus	3	1,109.9 NS	29.1 *	1,331.1 **	17,975.6 NS
Linear	1	275.8 NS	72.1 **	3,631.2 **	6,453.2 NS
Quadratic	1	162.1 NS	3.6 NS	152.0 NS	8,123.6 NS
Cubic	1	2,891.8 *	11.4 NS	210.0 NS	39,349.8 NS
Error	12	357.7	7.5	87.9	47,380.5
Total	15	508.2	11.8	336.5	41,499.5

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 124. Summaries of the analyses of variance of data shown in Table 36.

Sources	df	Plant responses				
		Yield	P	K	Ca	Mg
		-----	-----	-Mean squares-	-----	-----
				Inceptisol (herbage)		
Phosphorus	3	0.732 **	0.00388 **	0.79554 **	0.24716 NS	1.35792 **
Linear	1	1.321 **	0.00864 **	2.18375 **	0.58696 NS	2.45302 **
Quadratic	1	0.416 *	0.00189 NS	0.20002 **	0.03571 NS	0.88046 NS
Cubic	1	0.458 *	0.00111 NS	0.00285 NS	0.11880 NS	0.74028 NS
Error	12	0.069	0.00051	0.01575	0.07082	0.21902
Total	15	0.201	0.00119	0.17171	0.10609	0.44680
				Inceptisol (roots)		
Phosphorus	3	0.344 *	0.00968 **	0.06838 **	0.07286 **	0.18932 NS
Linear	1	0.186 NS	0.02716 **	0.20064 **	0.10781 **	0.00872 NS
Quadratic	1	0.562 *	0.00186 *	0.00246 NS	0.10704 **	0.33243 NS
Cubic	1	0.285 NS	0.00001 NS	0.00205 NS	0.00372 NS	0.22682 NS
Error	12	0.089	0.00031	0.00604	0.00800	0.47619
Total	15	0.140	0.00218	0.01851	0.02097	0.41882

Table 124. Continued

Sources	df	Plant responses				
		Yield	P	K	Ca	Mg
		Mean squares				
				Oxisol (herbage)		
Phosphorus	3	0.732 **	0.00388 **	1.80337 **	0.24716 *	0.01776 NS
Linear	1	1.321 **	0.00864 **	4.26129 **	0.58696 *	0.04429 NS
Quadratic	1	0.416 *	0.00189 NS	0.24880 *	0.03571 NS	0.00662 NS
Cubic	1	0.458 *	0.00111 NS	0.90002 **	0.11880 NS	0.00236 NS
Error	12	0.069	0.00051	0.03021	0.07082	0.02561
Total	15	0.201	0.00119	0.38484	0.10609	0.02404
				Oxisol (roots)		
Phosphorus	3	0.024 NS	0.00359 **	0.23504 **	0.22899 **	0.01289 NS
Linear	1	0.038 NS	0.00969 **	0.40716 **	0.53136 **	0.00618 NS
Quadratic	1	0.025 NS	0.00002 NS	0.19287 **	0.00649 NS	0.02623 NS
Cubic	1	0.010 NS	0.00105 NS	0.10509 *	0.14911 *	0.00626 NS
Error	12	0.032	0.00054	0.01986	0.02735	0.01383
Total	15	0.031	0.00115	0.06289	0.06768	0.01364

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 125. Summaries of the analyses of variance of data shown in Table 39.

		Plant responses			
Sources	df	Mn	Cu	Zn	Fe
		----------Mean squares----------			
		Inceptisol (herbage)			
Phosphorus	3	2,060.2 NS	3.0 NS	107.7 NS	18,271.1 NS
Linear	1	2,290.7 NS	2.7 NS	300.8 *	38,064.8 NS
Quadratic	1	3,457.6 NS	4.5 NS	15.2 NS	14,210.8 NS
Cubic	1	432.2 NS	1.7 NS	7.1 NS	2,537.7 NS
Error	12	864.4	1.4	47.6	25,376.5
Total	15	279.3	0.5	16.5	16,647.0
		Inceptisol (roots)			
Phosphorus	3	117,041.2 **	13.4 NS	1,044.6 NS	2,752,606.9 NS
Linear	1	259,763.8 **	0.1 NS	292.9 NS	5,331,498.0 NS
Quadratic	1	57,742.4 NS	23.4 NS	896.2 NS	632,961.9 NS
Cubic	1	33,617.5 NS	16.8 NS	1,944.6 NS	2,293,360.8 NS
Error	12	13,422.4	21.5	834.5	2,623,677.0
Total	15	34,146.1	19.8	876.5	2,649,463.1

Table 125. Continued

Sources	df	Plant responses			
		Mn	Cu	Zn	Fe
		--------Mean squares--------			
			Oxisol (herbage)		
Phosphorus	3	600,337.9 **	2.8 NS	4,117.2 **	25,499.8 *
Linear	1	1,343,678.1 **	0.4 NS	7,511.8 **	21,353.2 NS
Quadratic	1	347,367.5 **	4.2 NS	4,543.7 **	24,150.1 NS
Cubic	1	109,968.0 **	3.8 NS	296.2 NS	30,996.0 *
Error	12	2,278.2	9.1	141.3	6,235.0
Total	15	121,890.1	7.9	936.5	10,087.9
			Oxisol (roots)		
Phosphorus	3	317,881.2 **	115.1 NS	1,598.7 NS	5,477,282.9 NS
Linear	1	882,689.8 **	232.7 NS	3,087.9 *	15,516,802.0 NS
Quadratic	1	64,554.6 *	112.3 NS	777.4 NS	2,043.6 NS
Cubic	1	6,399.3 NS	0.2 NS	930.9 NS	912,913.1 NS
Error	12	7,950.7	50.0	481.9	7,189,843.0
Total	15	69,936.8	63.0	705.3	6,847,325.0

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 126. Summaries of the analyses of variance of data shown in Table 40.

		Plant responses				
Sources	df	Yield	N	P	K	Ca
		Mean squares				
Legumes Le	1	2.282 NS	0.01260 *	0.00350 **	0.53104 **	0.08167 **
Phosphorus P	2	0.879 NS	0.01396 **	0.00641 **	0.04372 NS	0.00260 NS
Linear	1	0.181 NS	0.02641 **	0.01266 **	0.08702 NS	0.00391 NS
Quadratic	1	1.577 NS	0.00152 NS	0.00017 NS	0.00041 NS	0.00130 NS
Le X P	2	0.230 NS	0.00108 NS	0.00115 **	0.01185 NS	0.00135 NS
Error	18	0.951	0.00195	0.00035	0.03590	0.00632
Total	23	0.940	0.00338	0.00108	0.05601	0.00884

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 127. Summaries of the analyses of variance of data shown in Table 41.

Sources	df	Plant responses				
		Mg	Mn	Cu	Zn	Fe
		-------------------------Mean squares	-------	-------	-------	-------
Legumes Le	1	0.84750 *	181.5 NS	6.0 NS	3.4 NS	1,480,066.7 NS
Phosphorus P	2	0.34936 NS	4,062.5 *	6.2 NS	475.2 **	1,927,737.5 NS
Linear	1	0.35701 NS	3,906.2 NS	4.0 NS	870.2 **	142,506.2 NS
Quadratic	1	0.34172 NS	4,218.8 *	8.3 NS	80.1 NS	3,712,968.8 NS
Le X P	2	0.07418 NS	283.5 NS	30.5 NS	33.5 NS	447,329.2 NS
Error	18	0.12313	895.8	15.4	26.1	3,510,502.8
Total	23	0.17004	1,086.9	15.5	64.8	3,018,228.3

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 128. Summaries of the analyses of variance of data shown in Table 42.

Sources	df	Plant responses				
		Yield	N	P	K	Ca
		Mean squares				
Legumes Le	2	240.048 **	0.50381 **	0.00188 NS	0.08095 NS	0.01491 NS
Phosphorus P	2	2.239 NS	0.03739 **	0.00762 *	0.04275 NS	0.01021 NS
Linear	1	0.510 NS	0.07042 **	0.01354 **	0.04950 NS	0.00510 NS
Quadratic	1	3.967 NS	0.00436 NS	0.00170 NS	0.03600 NS	0.01531 NS
Le X P	4	0.824 NS	0.00080 NS	0.00014 NS	0.02689 NS	0.00573 NS
Error	27	2.273	0.00225	0.00146	0.06366	0.02843
Total	35	15.692	0.03275	0.00168	0.05925	0.10836

* Significant F test at the 5% level.

** Significant F test at the 1% level.

Table 129. Summaries of the analyses of variance of data shown on Table 43.

Sources	df	Plant responses				
		Mg	Mn	Cu	Zn	Fe
		---Mean squares---				
Legumes Le	2	0.40343 **	34,560.0 **	336.2 **	1,140.4 **	23,280,678 **
Phosphorus P	2	0.00278 NS	318.4 NS	14.2 NS	47.4 NS	1,177,136 NS
Linear	1	0.00004 NS	0.7 NS	28.2 NS	88.2 NS	124,704 NS
Quadratic	1	0.00551 NS	636.0 NS	0.2 NS	6.7 NS	2,229,568 NS
Le X P	4	0.00597 NS	1,150.6 NS	2.9 NS	9.6 NS	943,340 NS
Error	27	0.01138	1,723.2	8.9	56.7	1,491,744
Total	35	0.03267	3,453.8	27.2	112.7	2,656,174

** Significant F test at the 1% level.

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Victor Manuel Urrutia R. was born on March 29, 1941, in Guatemala City, Guatemala, Central America. He attended high school at the Instituto Nacional Central de Varones in Guatemala City and graduated in 1959. In March, 1960, he entered the Escuela Agricola Panamericana in Honduras, C. A. He graduated with high honors in December, 1962, and was awarded the Wilson Popenoe Scholarship to continue studies in Agriculture. He worked at the Division of Tropical Research, La Lima, Honduras, from February, 1963, to August of the same year.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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